Scoping study: CCUS and circularity in building materials

TNO Publiek › TNO 2023 P10260
7 February 2023

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TNO 2023 P10260 – 7 February 2023

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Classification report	TNO Publiek
Report text	TNO Publiek
Number of copies	N/A
Number of pages	31 (excl. front and back cover)
Number of appendices	N/A

Contents

1 Background

The Ministry of Economic Affairs has requested TNO to build knowledge around the scope 3 emissions impacts of innovative industrial processes. Since last year, TNO has been assessing the full value chain greenhouse gas (GHG) emissions of certain innovative technologies in industry, including bio-based and circular value chains in the chemicals and refining sectors. As part of this study, the ministry has indicated their interest in carbon capture and utilisation (CCU) and circularity in building materials. This scoping study was conducted about those options, with a focus on cement and concrete value chains.

The objective of this study was to identify promising value chains within the building materials sectors for further analysis via life cycle assessment (LCA). Two possibilities were identified in scoping this work: carbon capture and utilisation in concrete production and increased circularity in cement and concrete value chains. The scoping study aims to determine whether it would be worthwhile to conduct an LCA of these value chains, and if so, which cases would be the most useful to analyse from the perspective of reducing life cycle emissions from Dutch industrial activities.

2 Cement and concrete sector

2.1 General background

Concrete is the world's most-used building material, used in everything from residential and commercial buildings to energy infrastructure to roads, bridges, and dams. In 2021, about 4 300 Mt of concrete's main ingredient, cement, was produced (IEA, 2022a), and the direct (Scope 1) emissions from this production accounted for about 7% of global CO_2 emissions from energy use and industrial processes (IEA, 2022a)(IEA, 2022b).

Figure 1 below, shows a simplified diagram of the concrete production process. The main raw material input is limestone, quarried, crushed, and sent to a kiln for calcination. Calcined limestone is called "clinker"; this forms the active hydraulic ingredient in cement. Clinker is blended with gypsum to make cement. Clinker can also be partially replaced by substitute products. The most common of these today are blast furnace slag and fly ash (which are waste products from ironmaking and from coal combustion), but ground limestone, natural pozzolanic material, and other substitutes can also be used.

European standards define several categories of cement products depending on their composition and performance (Cembureau, 2022):
- CEM I Portland cement (>95% clinker)
- CEM II Portland-composite cement (65-94% clinker)
- CEM III Blast furnace cement (5-64% clinker)
- CEM IV Pozzolanic cement (45-89% clinker)
- CEM V Composite cement (20-64% clinker)

Cement is mixed with other mineral ingredients, mainly crushed stone, to form concrete (with the exception of smaller amounts used to produce mortar). Concrete is then sold primarily as either precast or ready-mix. Precast or prefabricated products are cast into standardised shapes, cured in place and transported to a construction site to be immediately lifted into place. Ready-mix concrete is produced at a batch plant and transported by truck mixer to construction sites, where it is cured in place (Cembureau, 2022).

As cement is a relatively low-cost product relatively to its weight, it is typically produced close to where it is used. It is therefore rare that cement is shipped or traded, except between neighbouring countries. Concrete is produced even closer to its final destination, as it is even more costly to transport after either curing or mixing with water and aggregate.

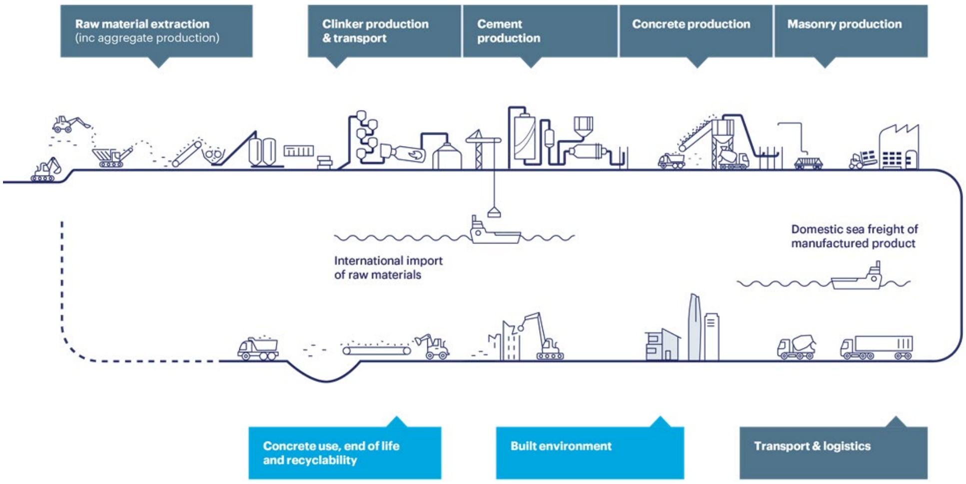

Figure 1 Cement and concrete production (ADBRI, 2022)

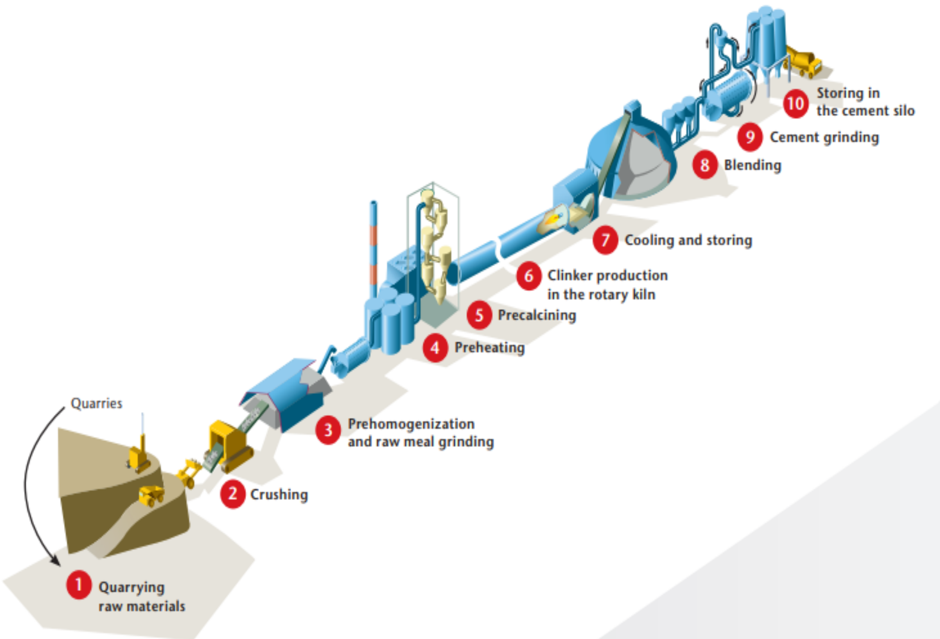

Figure 2 Cement production processes (IEA and CSI, 2019).

The clinker production process, represented by steps 2-7 in Figure 2, is by far the most energy- and emissions-intensive step in this value chain. Raw materials must be heated to about 1450°C in the kiln; on average, this requires about 3.5 GJ thermal energy input per tonne of clinker (IEA, 2022). Furthermore, about two-thirds of the total direct CO_2 emissions from cement production are released in the calcination reaction which converts limestone into calcium oxide in the kiln. For the case of Ordinary Portland Cement (OPC/CEM I), clinker makes up about 11% of concrete by mass, but is responsible for about 95% of the Scope 1 emissions[1] from concrete production (Material Economics, 2019).

[1] This represents the share not on a life cycle basis, but only considering emissions from the manufacturing processes of clinker, cement and concrete. Other emission sources such as transport are not included here

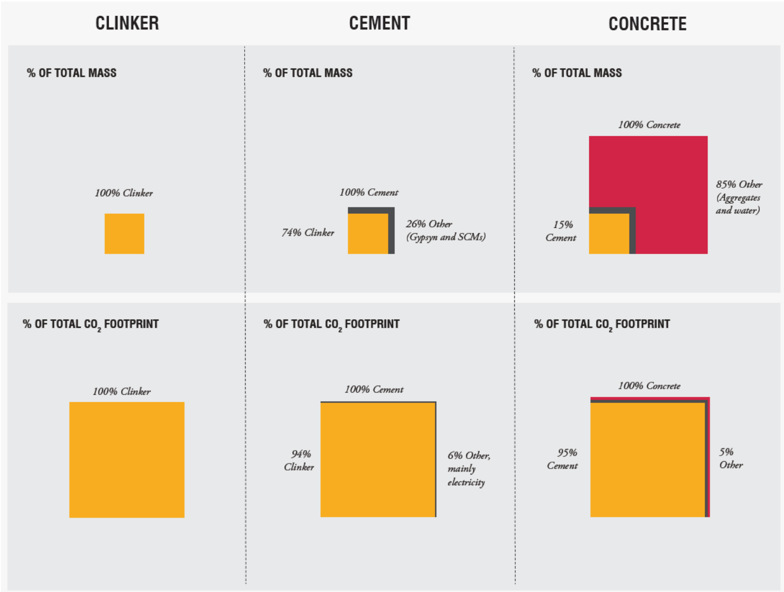

Figure 3 Clinker, cement and concrete by mass and CO_2 footprint (Material Economics, 2019).

The Dutch context

In the Netherlands, cement is produced at two sites, in Rotterdam and IJmuiden, both owned by Eerste Nederlandse Cement Industrie (ENCI), with a capacity of about 2 Mt/year. These sites do not produce clinker, but dose and grind raw materials to create mainly CEMI and CEMIII products (steps 8-10 in Figure 2). The company also operated a site in Maastricht, which was shut down in 2020, and until 2019 also produced clinker. Currently, no clinker is produced inside the Netherlands; clinker used to produce cement in the Netherlands is imported, mainly from Belgium (Xavier and Oliveira, 2021)[2].

However, significantly more cement is consumed in the Netherlands than is produced, so in addition to clinker imports, cement is also imported. Cement consumption in the Netherlands in 2019 was about 5.1 Mt, or about 0.3t per capita (Betonhuis, 2020)(CBS, 2022a).

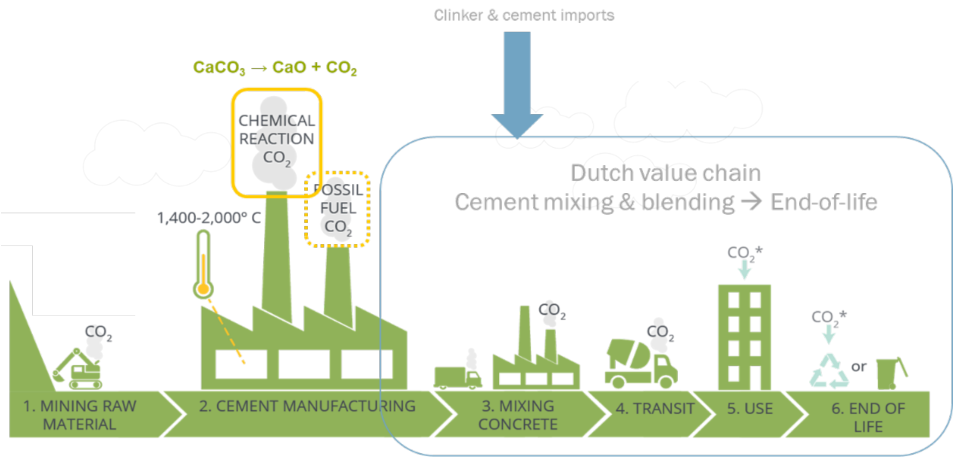

Figure 4 Cement consumption in the Netherlands, 1999-2019. Adapted from (Carbon Smart 2022)

[2] Additional, detailed information about the current Dutch cement sector can be found in Xavier and Oliveira, 2021 and in the MIDDEN database (PBL and TNO, 2022).

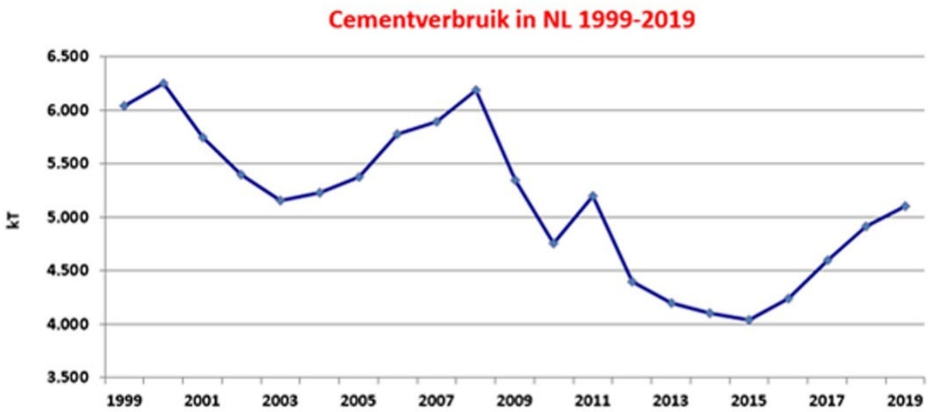

Figure 5 Cement consumption in the Netherlands, 1999-2019. (Betonhuis, 2020).

This is in line with consumption levels in other developed economies. See below in Figure 6 the evolution of consumption per capita for G20 countries versus GDP per capita; with some exceptions, the cement consumption is generally expected to stabilize as GDP per capita increases. However, fluctuations are also observed in historical data, as cement demand decreases during times of recession, and increases during recovery; this is highly correlated with activity in the construction sector. Nitrogen emission policy also played a role in recent years in Dutch cement and concrete consumption, leading to a 5% decrease in cement use in the Netherlands in 2020, and a recovery of 1% in 2021, to remain around 5 Mt (Cembreau 2021).

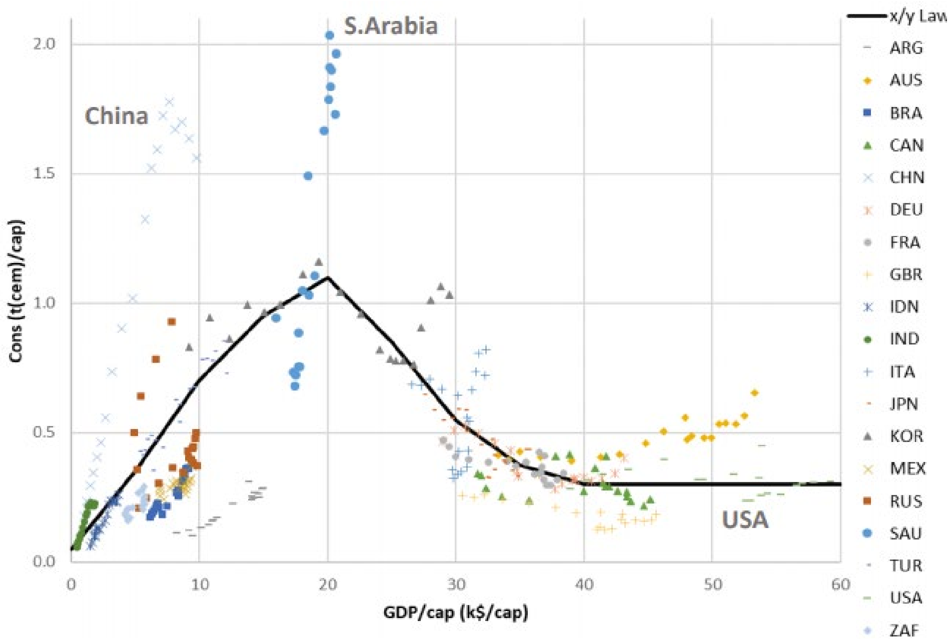

Figure 6 Cement consumption per capita and GDP per capita in the G20 countries (Keramidas et al., 2021)

Cement and clinker imports to the Netherlands have been relatively stable in recent years, mirroring total cement consumption until about 2015; after 2015, the relatively constant clinker imports while consumption grew can be partially attributed to the growing share of low-clinker content cements, for example CEMIII/A which contains less clinker than CEMIII/B (Figure 7, Figure 8).

Tabel 4 - Verdeling van het cement naar cementtypen in betonmortel, betonproducten en 'beton totaal'

	Betonmortel (%)			Betonproducten (%)			Beton totaal (%)		
Cementtype	1990	2010	2017	1990	2010	2017	1990*	2010	2017
CEM I	--	21%	19%	--	53%	56%	36%	34%	36%
CEM II	--	2,8%	4,0%	--	2,2%	12%	7,0%	2,6%	7,6%
CEM III/A	--	0%	1,7%	--	26%**	30%	0,0%	10%	15%
CEM III/B	--	75%	71%	--	16%**	1,7%	57%	52%	40%
CEM IV	--	0%	0%	--	0%	0%	0%	0%	0%
CEM V	--	0,4%	4,0%	--	3,6%	0,0%	0,0%	1,7%	2,2%

Figure 7 Shares of cement types in total concrete products in the Netherlands (CE Delft 2022)

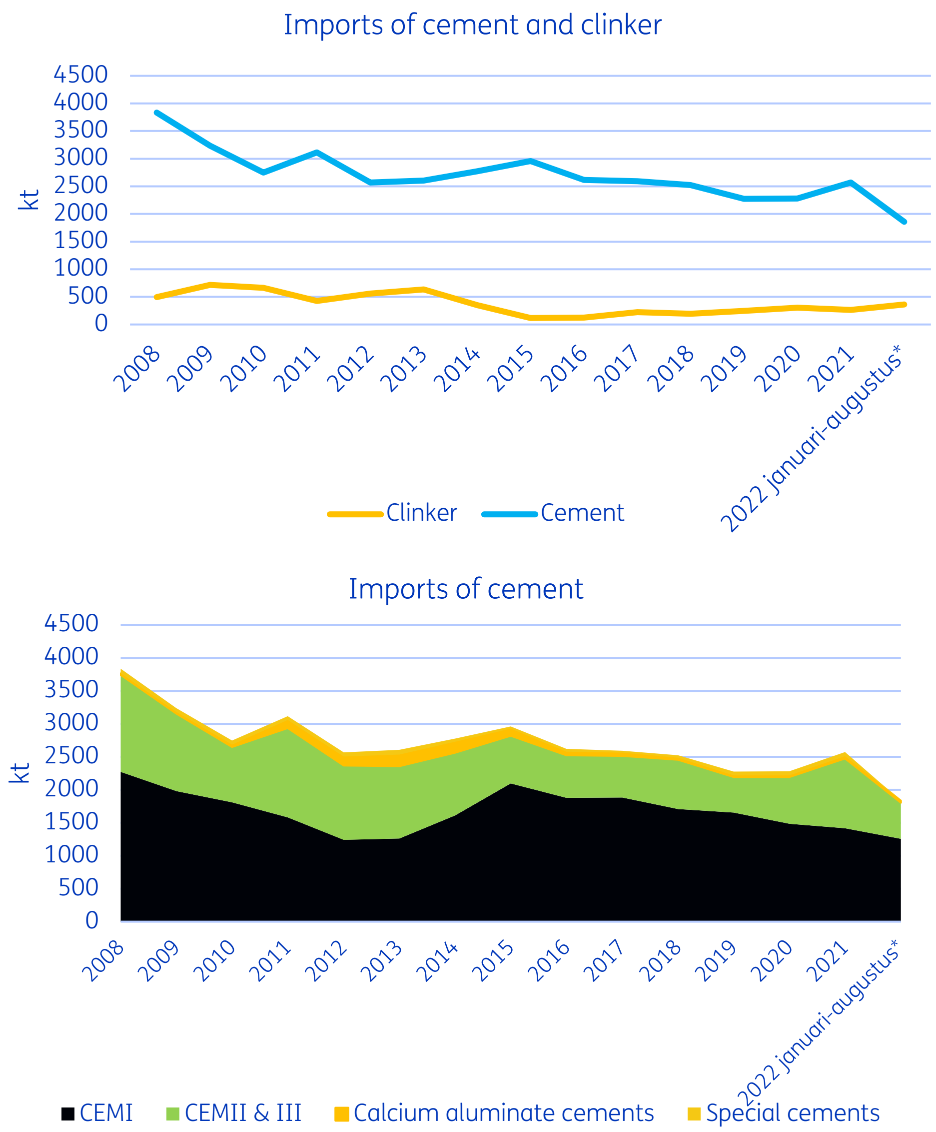

Figure 8 Cement and clinker imports, 2008-2022 (CBS 2022b)

According to a study by CE Delft, the Dutch construction sector used about 33 kton concrete in 2010, of which almost 14 kt was used for civil engineering works (Figure 9). However, up-to-date public information about cement and concrete consumption is limited; what is available is typically based on derived estimates provided by companies.

Tabel 3 Berekende hoeveelheden beton en wapeningsstaal, toegepast in de Nederlandse bouw, 2010

Berekende waarden op basis van gegevens van VOBN en BFBN	Totale hoeveelheid	Woningen	Utiliteits-bouw	GWW/Civiel/ Agrarisch/ Overig
Totaal beton (kton)	32.751	9.216	9.726	13.809
Betonmortel (kton)	18.438	6.789	5.871	5.778
Betonproducten (kton)	14.314	2.428	3.856	8.030
Wapeningsstaal (kton) Hoog*	546	198	229	119
Laag*	470	160	191	119

* Omdat de hoeveelheid wapeningsstaal binnen toepassingen (vloeren, muren, etc.) kan verschillen is er gewerkt met een range, wat leidt tot een hoge en lage inschatting van de hoeveelheid wapeningsstaal.

Figure 9 Total concrete and reinforcing steel use in the Dutch construction sector, 2010 (CE Delft 2013)

As a result of the large share of imports, the emissions impact from Dutch cement and concrete production and consumption occurs largely abroad. Xavier and Oliveira, for example, estimated that about 85% of emissions from Dutch cement production were related to clinker produced outside of the Netherlands (Figure 10). This excludes emissions from raw material extraction, transport, and cement that is fully produced outside the Netherlands.

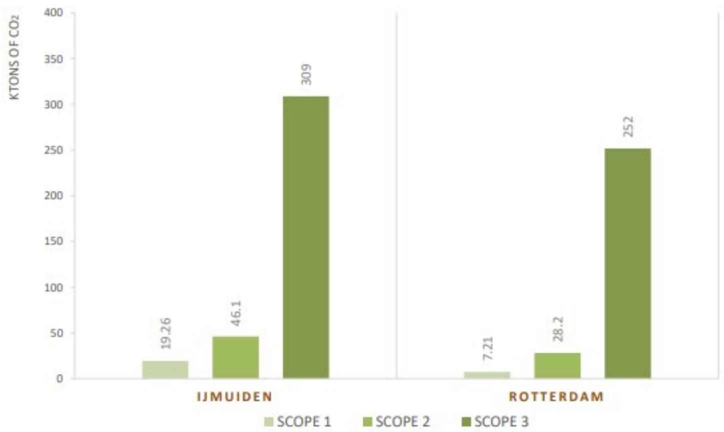

Figure 10 Scope 1, 2, and 3 emissions from Dutch cement production (Xavier and Oliveira, 2021)
Note: The report calculates Scope 2 emissions as CO_2 emitted in off-site electricity generation, and the Scope 3 emissions shown in the figure above include only emissions from clinker production outside of the Netherlands.

2.2 Reducing GHG emissions from cement & concrete

Broadly speaking, the options for reducing greenhouse gas emissions from the cement and concrete value chain fall into several categories, and can be mapped as shown in Figure 11**Fout! Verwijzingsbron niet gevonden.** below. In the following section we present a brief overview of key options for reducing greenhouse gas emissions from the cement and concrete value chain, and their relevance to the Netherlands.

	Mining & quarrying	Clinker production	Cement grinding & blending	Concrete mixing & curing	Transport	Utilities	Use
Location	Outside NL	Outside NL	NL	NL	NL	NL	NL
Energy efficiency	x	x	x	x	x	x	x
Fuel substitution	x	x			x	x	
Carbon capture		x				x	
Material substitution			x	x			x
Circularity							x
Demand reduction & material efficiency	x	x	x	x			x
Re-carbonation				x			

Figure 11 Categories of emission reduction options for the cement and concrete value chain

Energy efficiency

Energy efficiency can be applied at all steps of the value chain, in order to incrementally reduce emissions from energy use. Kilns are the largest user of thermal energy in this value chain; variations in thermal energy intensity performance within Europe are large, and globally are even larger. State of the art performance is achieved using preheaters and precalciners, and large kiln capacity. Waste heat can also be reused for preheating purposes on-site to reduce overall fuel consumption. Efficient power and heat generation is also an important factor. Improvements in electrical efficiency can be found by implementing efficient grinding technologies for raw materials and for clinker, in particular. The European Cement Research Academy (ECRA) published a set of papers describing the state of the art along with costs and performance for various new technologies (CSI and ECRA, 2017).

Efficiency improvements can also be found in transport and utilities operation, on a case-by-case basis. The RVO list of recognized energy saving measures for the building materials sector provides an indication of common energy saving measures (RVO, 2019). As no kilns are operational in the Netherlands, the focus is on efficiency in power generation, grinding, mixing, and transport.

Fuel substitution

Use of alternative fuels applies to transport vehicles, mining and quarrying machinery, clinker production in the kiln, and power and heat utilities can all reduce emissions in the cement and concrete value chain. Clinker production in the kiln accounts for the largest share of thermal energy use in these sectors. For the kiln, electrification is being investigated but remains at small scale (experiments by VTT) (Katajisto, 2022). Substitution of biomass and waste-based fuels can reduce combustion emissions compared to coal and petroleum coke, which are the most commonly used fuels today, but will not address process emissions. There are no operational kilns in the Netherlands, so this option will only apply to domestic transport of cement and concrete products. More generic options for low-carbon fuels for power and mobility are the main options for the Netherlands.

Carbon capture

For clinker production in kilns, several options for capturing CO_2 emissions exist, including post-combustion capture from kiln flue gases using chemical absorption, membranes, or calcium looping; oxy-fuelling with carbon capture; direct separation technologies; or calcium looping during combustion. Capturing CO_2 during cement production is most efficient when applied to the highest concentration of point-source CO_2 which comes from the kiln; this is a mix of CO_2 from fuel combustion and process emissions released during the calcination reaction (CSI and ECRA, 2017) (IEA and CSI, 2019).

However, cement and concrete production sites also use heat and power generated by utilities (either on- or off-site); when these utilities run on carbon-containing fuel, CO_2 can also be captured. As no clinker kilns are operating in the Netherlands, CO_2 capture is only applicable to the power and heat utilities serving the sector. As this does not specifically target the building materials sector, but rather utility technologies that are broadly used in a variety of energy and industrial sectors, this option is not further discussed here.

Carbon captured from other point sources can also be sequestered in concrete as it cures, taking advantage of natural reactions in order to reduce the emissions footprint of concrete. Carbon can be added to ready mix concrete at the mixing stage, allowing it to be used for ready-mix deliveries. There are also possibilities to allow precast concrete products to “cure” – or harden – in a CO_2 -rich environment, so that the concrete can sequester some carbon before its use in a structure. These possibilities are discussed in more detail below.

Clinker substitution

Clinker – the most CO_2-intensive part of cement and concrete products – can be partially or fully replaced by substitute materials, called supplementary cementitious materials (SCMs). Historically, fly ash from coal power plants and blast furnace slag from the steel sector have been used in many alternative cements (CEM II and CEM III respectively), alongside natural and artificial pozzolanic materials, and natural and artificial fillers (see Figure 12).

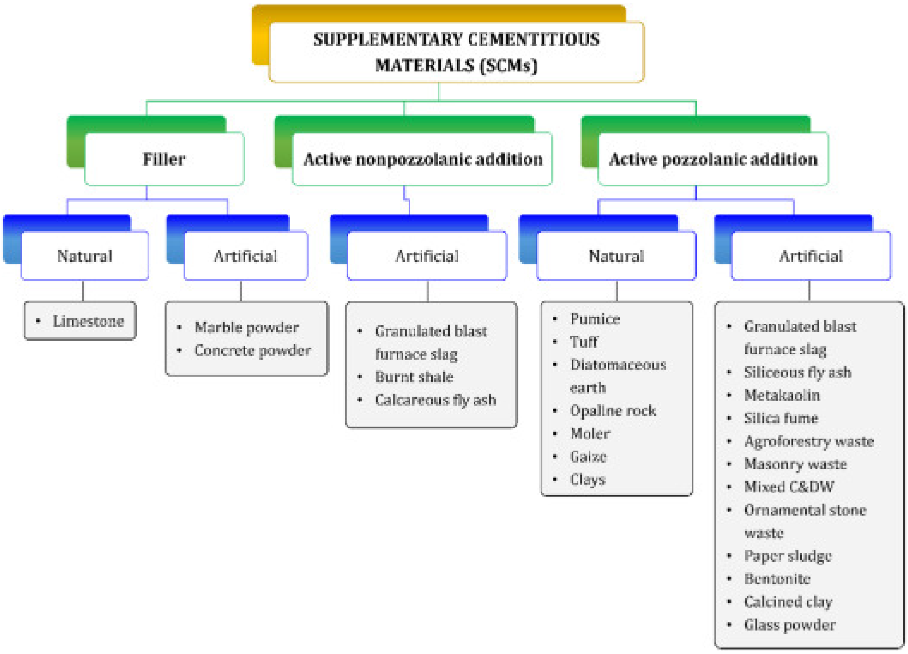

Figure 12 Common supplementary cementitious materials (SCMs) (Martinez et al., 2021)

The long-term availability of blast furnace slag and fly ash in particular is not compatible with low-emissions scenarios, and as demand for lower-carbon cement and concrete grows, the supply will not be sufficient to scale up (IEA, 2022). Scrivener et al. describe in detail the current status of the main types of supplementary cementitious materials and fillers, both from the perspective of technical performance and long-term prospects and availability (Scrivener, et al., 2018). The extent of substitution possible is dependent on the performance requirements of the final application of cement and concrete. Further many of these SCMs require processing, which may also lead to additional energy use and emissions. However, the life cycle emissions performance of these SCMs, particularly those which are widely available and technically promising, merits further investigation.

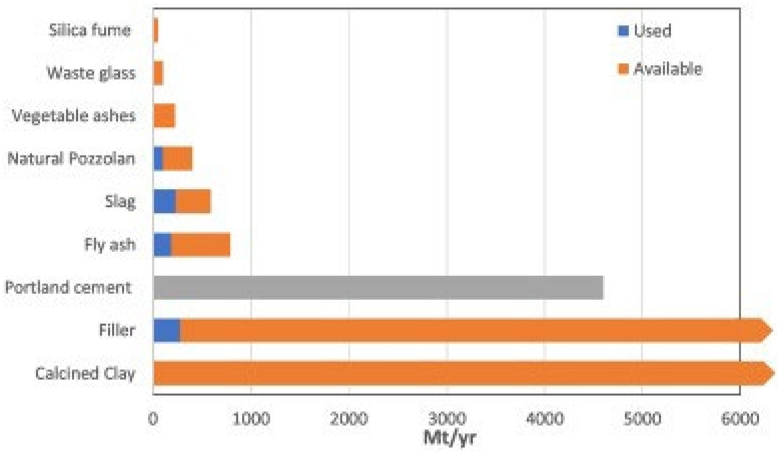

Figure 13 Use and estimated availability of possible SCMs and fillers (Scrivener et al., 2018)

Though more data on particular applications would be needed to determine the lifecycle emissions impact of these SCMs in the Netherlands, it is clear that clinker substitution is a relatively low-cost emissions abatement option for the cement and concrete sector. In

2020, the global average clinker-to-cement ratio was 0.72; IEA's Net-Zero Emissions scenario requires this to fall to 0.65 by 2030 (IEA, 2022). In the Netherlands, reducing clinker content in domestically produced cement could reduce Scope 3 emissions which occur in the production of clinker abroad (though this should be balanced with any potential increases in emissions in the production of SCMs). Blast furnace slag, in particular, would likely become more scarce and costly in the Netherlands if Tata Steel goes ahead with plans to phase out blast furnace-based ironmaking in favour of direct reduction.

Circularity

Currently, concrete waste from demolition of buildings and infrastructure is typically crushed and "downcycled" into aggregate for road beds or for mixing into new concrete. Other options, like reuse of whole concrete elements in new construction, and recovery of cement from end-of-life concrete, are discussed and investigated, but not broadly commercially applied. Logistical barriers and lack of financial incentives mean that even known circular options are not often taken up. This is reflected in the small estimated potential in both IEA and Material Economics scenarios for the cement sector, and in the estimated CO_2 reduction potentials described in the roadmap from the Betonakkoord (IEA and CSI, 2019) (Material Economics, 2019) (Betonakkoord 2021). Nonetheless, companies like New Horizon Urban Mining are aiming to reshape the construction and demolition sector of the Netherlands to increase circularity for cement and concrete as well as other building materials. The options for reuse and recycling are discussed further later in this chapter.

Demand reduction & material efficiency

Reducing overall demand and reducing material losses would reduce emissions all along the value chain (in absolute terms and in some cases, in specific terms as well). This includes reducing the amount of clinker in cement (see clinker substitution above), reducing the amount of cement in concrete, reducing the amount of concrete in a structure, and reducing the demand for concrete structures. This can include reductions in losses and waste in manufacturing and construction, as well as avoiding overspecification of cement and concrete for their final applications. Lifetime extension of concrete structures and repurposing of existing structures would also reduce the demand for new clinker, cement and concrete. Some of these possibilities are strongly related to other emission reduction options; for example, reuse of concrete elements at the end of their lifetime reduces the demand for virgin clinker, cement and concrete, and high-performance concrete with CO_2 sequestration could potentially also reduce the demand for more energy- and emissions-intensive products if less product is needed to meet structural requirements.

Many of the demand reduction and material efficiency measures available in this sector would require regulatory work at the national and European level – for example, building standards may need to be adapted, for example, to allow for more efficient use of material to meet structural requirements. Advanced fillers are able to reduce the amount of cement needed in concrete, while achieving required compressive strength – reducing "binder intensity" – but EU standards for concrete specify minimum cement content for each concrete class, rather than setting requirements for performance indicators (Material Economics, 2019).

Further, scaling up demand reduction and material efficiency would also require novel approaches to designing and building structures, from architects to construction crews. Ready-mix concrete today often contains 20% more cement than is required by standards, in order to correct for incorrect use at construction sites. Often, in order to simplify logistics and procurement, one class of concrete is used throughout a project, rather than matching structural needs to cement requirements, which leads to overuse of cement (Material Economics, 2019).

However, many researchers agree that the potential is large. In IEA scenarios, there is a large global potential for demand reductions resulting mainly from lifetime extension, related to building retrofits for energy efficiency. Demand is reduced even further by aggressive reductions in overspecification and reducing waste in the Material Efficiency scenario (IEA, 2019). An analysis of material efficiency potential in the EU found that a stretch scenario for material efficiency could reduce cement demand by 65% compared to current practice, through a combination of measures reducing cement in concrete and concrete in structures (Material Economics, 2019).

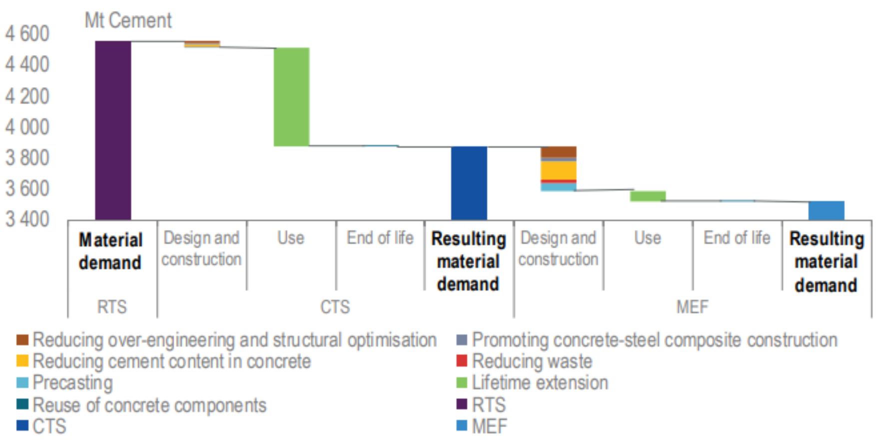

Figure 14 Reduction in cement demand in IEA scenarios (IEA, 2019)

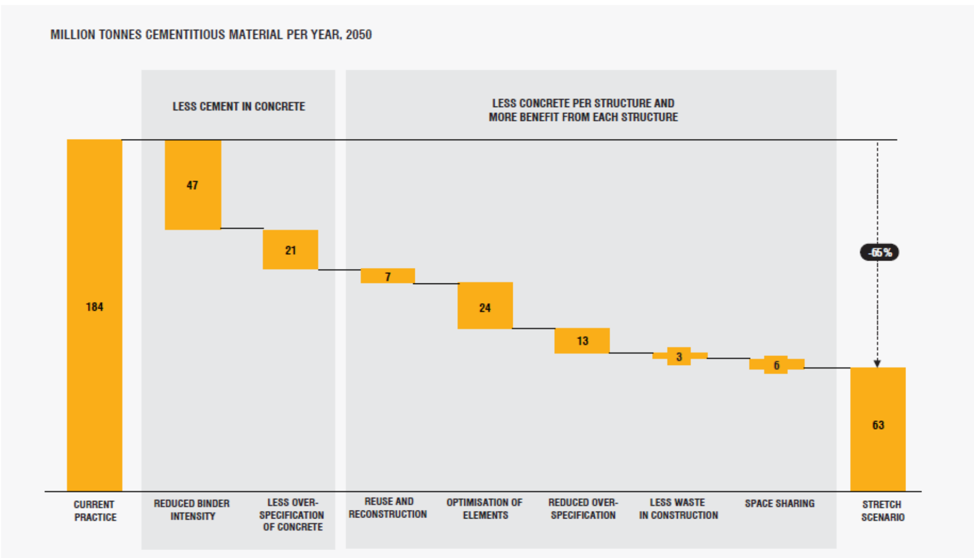

Figure 15 Reduction in cement demand in 2050 (Material Economics, 2019)

Demand reduction in the Dutch market and efficiency in domestic cement and concrete use could have emission reduction benefits in the Netherlands, related to reduced concrete production and cement grinding, as well as abroad, related to reduced clinker production. In the Betonakkoord CO_2 Reduction Roadmap, several options are named explicitly; for example, lifetime extension of existing structures is estimated to have a potential to reduce

CO_2 emissions in 2030 by 117 ktCO_2/year, and design optimisation to have a 200 ktCO_2/year potential (Betonakkoord 2021).

Alternative products

Alternative materials, such as cross-laminated timber, brick, or alternative binding materials with cementitious properties, can in some cases provide the same structural service that is currently provided by cement and concrete. This requires engagement and participation from architects, engineers, the construction sector, regulatory agencies, and end-users to ensure that structures built from alternative materials are safe, functional and comfortable.

Alternative binders, a category of materials with similar properties to cement but which produce less emissions during production, covers a variety of materials. Some of the most commonly discussed are alkali-activated binders (also called geopolymers) rely mainly on industrial byproducts with cementitious properties. Others are based on alternative raw materials, often reducing process emissions by reducing the calcium present in the raw mix. Each binder has slightly different characteristics (for example, when it comes to reaction speed and compressive strength), making each suitable for different applications (GCCA 2022a). The Betonakkoord, an agreement of concrete and construction sector stakeholders, finds significant potential for CO_2 reductions from various alternative binders by 2025-2030, quantified in their 2021 CO_2 Reduction Roadmap (Betonakkoord 2021).

For example, ASCEM Special Technologies in the Netherlands produces an alkali-activated binder (or geopolymer) product by melting secondary resources such as siliceous fly ash. This forms a reactive glass with binding qualities, which makes up about 50% of the total mass of the final binder product, while the remaining 50% is made up fly ash as filler. It has similar compressive strength performance to CEM III (based on ground blast furnace slag) and Portland cement, and reduced emissions compared to conventional cement products. However, availability of fly ash, which is sourced mainly from coal combustion in power plants, will decrease as the energy transition progresses, and as Dutch coal-fired power plants shut down. Additionally, while fly ash is a secondary resource, its use in ASCEM binders does not create the possibility for a closed-loop circular product.

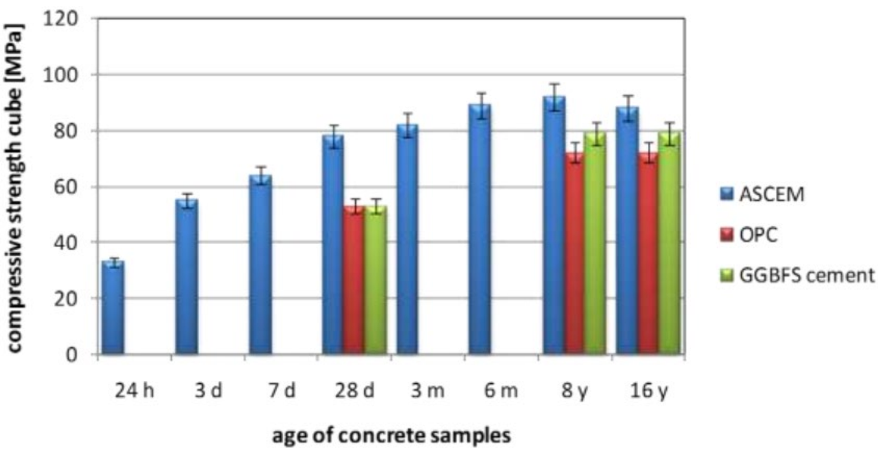

Figure 16 Compressive strength of ASCEM binder versus OPC and blast furnace slag based cement (Buchwald and Wiercx, 2012).

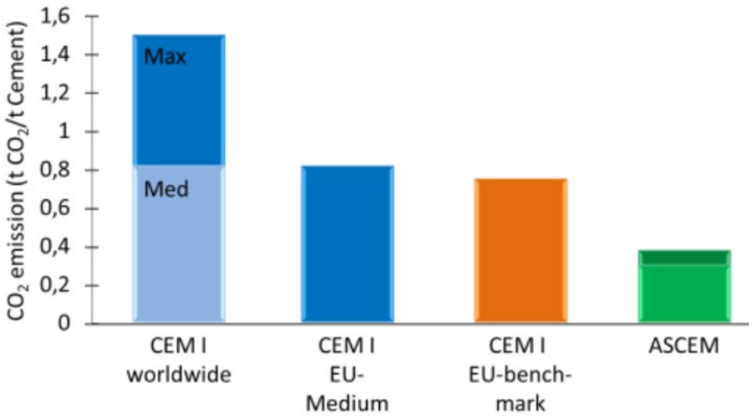

Figure 17 Specific CO_2 emissions for ASCEM binder versus CEM I (Buchwald and Wiercx, 2012)

Publicly available information about the latest developments of ASCEM binder technology is limited, but ASCEM claims that its latest binder products reduce CO_2 emissions by 80 to 90 percent compared to Portland cement, and that they use 85% reused materials, though specific materials are not specified. These claims are more ambitious than those in their 2012 publication, but they could not be verified based on academic papers or detailed public information (ASCEM Special Technologies, 2022).

It is also worth noting a few start-ups and lab-scale developments, which are further from commercialisation but give an impression of the variety of possible options which may eventually come into play. While this list is not exhaustive, some examples includeTerraCO2, which has built several pilot plants for their alternative cementitious material that is produced from silicates at a lower temperature than Ordinary Portland Cement clinker (Yearsley & Lake, 2022). This is an alkali-activated binder (or geopolymer); other companies are also active in this space.

Brimstone, a US-based start-up which has announced a project to build a pilot plant to produce clinker from calcium silicate instead of limestone, avoiding process emissions while producing a cement that is chemically identical to Portland cement produced from limestone. The technology is currently at lab scale (IEA, 2022). If scaled up, this technology could eventually dramatically reduce CO_2 emissions in the production of clinker. Currently, public information about the process is limited.

A variety of other alternative materials with cementitious properties are under development around the world – for example, Prometheus Materials aims to harness micro-organisms, like algae, that can precipitate calcium carbonate from CO_2 – a process called biomineralisation, similar to how an oyster or a clam would produce its shell – which then forms the basis of “bio-concrete” (Edwards, 2022).

Any options involving alternative materials would require life cycle assessments in order to determine their full impacts on Scope 1, 2 and 3 emissions compared to conventional cement and concrete products. Such an LCA would also require significant amounts of data and assumptions – for example, on how to allocate the emissions related to waste products and byproducts from other sectors which are used as material or fuel in the cement & concrete sector. Further, the long-term availability of key raw materials is an important consideration. Binders based on fly ash from coal power plants are unlikely to find a long-term and cost-effective supply of the necessary raw materials in the Netherlands.

2.3 CCUS in the Dutch cement and concrete sector

The following chapters will focus on the two main areas of focus of this scoping study: CCUS and circularity. The figure below gives an overview of the key options discussed.

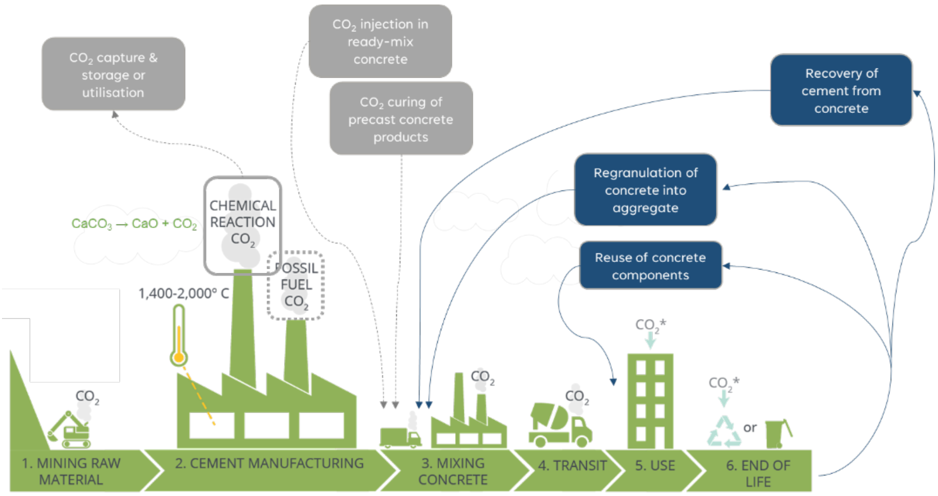

Figure 18 CCUS and circularity options discussed in the following chapters. Adapted from (Carbon Smart, 2022)

Carbon capture

Carbon capture, with eventual storage or utilization, is a relevant emissions reduction option wherever stationary point sources of CO_2 are emitted. Within the cement and concrete value chain, this is relevant for power and heat production and clinker kilns. Here, combustion occurs and significant point sources of emissions are produced, which may be feasibly captured. Capturing CO_2 requires additional energy use, referred to as an "energy penalty," in turn increasing primary energy demand of the plant. The options for carbon capture in power and heat are well-studied, and would reduce Scope 2 emissions from the cement and concrete sector. Clinker kilns are an interesting candidate for CO_2 capture due to the high concentration (around 20 vol%) of CO_2 in their flue gases for efficiently operated kilns (IEAGHG, 2013). This makes carbon capture more technically and economically attractive. There is extensive literature examining the costs and feasibility of applying CO_2 capture to cement kilns. Several projects are under construction and set to become operational in the next few years: the LEILAC project at a HeidelbergCement plant in Hanover, which uses a direct separation technology (LEILAC, 2022), and Norcem's Brevik plant, which uses amine solvent technology to separate CO_2 from flue gases (Norcem, 2022). However, as no kilns are currently operating in the Netherlands, since the ENCI Maastricht site shut down in 2020 (ENCI, 2022), this option is unlikely to play a role for the Dutch building materials sector.

Carbon sequestration in concrete

Captured CO_2 could also be used as an input to concrete production in the Netherlands. Cement naturally absorbs some CO_2 from the atmosphere as it cures and over its lifetime, both via reaction of free lime with CO_2 to form calcium carbonate, and of calcium silicate hydrate with CO_2 to form silica gel (GCCA, 2022b). This reaction occurs only near the surface of the concrete. Crushing concrete at the end of its lifetime can increase surface area and speed up this reaction, but uncertainties remain around the exact rate of recarbonation of concrete, and the use of the crushed concrete also plays a role. This has not generally been considered as a major source of emission reductions, but it does provide some CO_2 emission reductions. Currently, the CO_2 uptake of concrete products is not considered in IPCC emissions calculation guidelines, but proposals from stakeholders in the cement and concrete industry have been put forward, including a proposal based on the Dutch situation (Stripple, H., et al., 2018).

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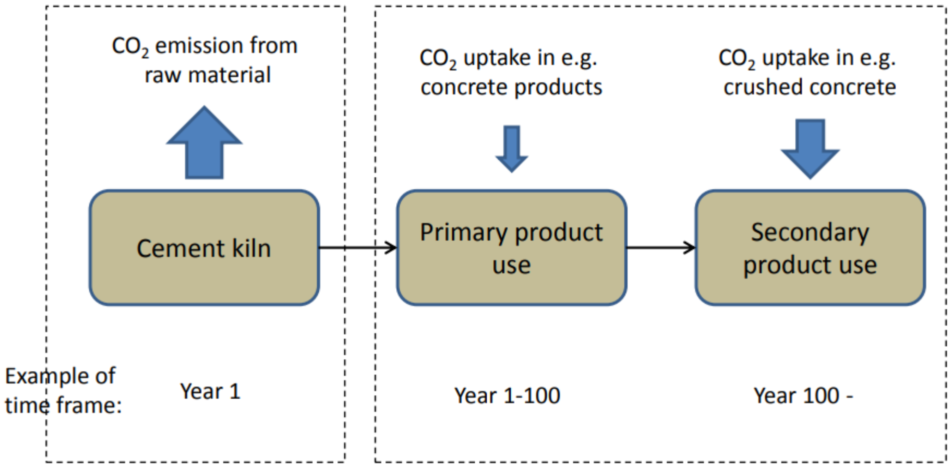

Figure 19 Conceptual view of recarbonation reaction (Stripple, et al., 2018)

Some techniques aim to make use of the carbonation reaction to increase the speed of uptake and the amount of carbon stored in in-use concrete products. There are a variety of concepts under investigation, but the two most widely researched are 1) mixing high-purity CO_2 into fresh concrete where it binds with calcium silicate (CarbonCure, 2022b), and 2) curing precast concrete products in a high-pressure, CO_2-rich environment, allowing unhydrated minerals to react with CO_2 to form carbonates (Li et al., 2019) (Shao et al., 2006). While there seems to be potential for emission reductions, public data on the life cycle impacts of these products is limited, and some questions about the long-term potential remain.

1. *CO_2 injection in ready-mix concrete*
   This process involves injecting CO_2 into ready-mix concrete. The CO_2 then reacts with calcium ions to form calcium carbonate, which stores CO_2 in the final concrete product.

   Despite its benefits in terms of direct CO_2 utilization, Monkman and MacDonald also note that the benefits of reduced cement use (due to improved compressive strength of concrete) are far greater than the CO_2 that is sequestered (Monkman & MacDonald, 2017). CarbonCure, a US-based company producing concrete based on this method, makes a similar claim: for every m^3 of ready mix concrete produced using this method, about 0.3 kg of CO_2 is mineralized in the concrete, compared to 11.7 kg of avoided CO_2 due to reduced cement use (CarbonCure, 2022).

   Ready-mix concrete with CO_2 injection is being used in the renovation of the headquarters of De Nederlandsche Bank in Amsterdam. In combination with recycling of end-of-life concrete products (discussed further below), the project claims that its concrete production is fully CO_2-neutral (De Nederlandsche Bank, 2022). While calculations are not publicly available, and it is not specified which scope of emissions is considered, this seems to be based on the capture of biogenic CO_2 emissions from water purification processes to be injected into the concrete, which offset some of the remaining CO_2 emissions from the concrete production. Fully CO_2-neutral concrete at the value chain level would require either greater offsets or fully CO_2-neutral energy and raw material production.

2. *CO_2 curing of precast concrete products*
   Typically, concrete products are "cured" - the process by which concrete hardens – naturally in the air, either on a construction site, in the case of ready mix concrete, or at a manufacturing facility, in the case of precast products. This process involves curing concrete products in a controlled, high-pressure atmosphere of high-concentration CO_2, so that unhydrated cement minerals react with CO_2 and solidify into carbonates, effectively sequestering the CO_2.

   Some research indicates that CO_2 curing could increase durability, but potential increased risk of steel reinforcement corrosion requires more research (Li et al., 2019). Compressive strength develops more quickly than in conventional concrete products, and water consumption is reduced as well. However, some studies indicate that CO_2 curing can reduce the compressive strength of concrete in the long term; this would necessitate increased cement use in the concrete which increases emissions and can offset emissions benefits of CO_2 use in curing.

   This process is only applicable for precast concrete, where the curing environment can be controlled. Material Economics estimates that precast concrete applications account for 28% of the total use of cement in buildings and infrastructure in the EU (Material Economics, 2019). Solidia, a US-based company, has commercialized its precast concrete process, producing precast concrete blocks and pavers in both the US and Europe. In addition to savings from their patented "Solidia Cement" (an alternative binder similar to Portland cement which can be produced with lower temperatures than OPC clinker), Solidia claims that its precast concrete products can sequester 240 $kgCO_2$ per tonne of concrete (Solidia Technologies, 2022). Their patents claim 250-300 $kgCO_2$ sequestered per tonne of cement produced (Hanifa et al. 2023). Li et al. found an experimental CO_2 uptake value of about 15% (on a mass basis) after 28 days (Li et al. 2019).

3. *Other approaches*
   There are a few other approaches at even earlier stages of experimentation and development (Hanifa et al. 2023). These include CO_2 sequestration in alternative binders based on magnesium oxide, CO_2 dissolution in cement mixing water, and carbonation of recycled concrete aggregates. There is not yet sufficient data at large enough scale to make robust LCA studies of these options.

A recent life cycle assessment, comparing 99 published experimental datasets, finds that CO_2 utilization in concrete mixing and curing does not consistently result in a net climate benefit, though authors noted that variations in lifetime and geographic-specific factors warrant future research for specific applications (Ravikumar et al., 2021). Though both techniques are still in early stages of commercialisation, if the technology is scaled up, its impacts on emissions from Dutch concrete production and use would warrant a more detailed life cycle assessment, with consideration for the Dutch climate conditions, specific applications, and building/infrastructure lifetime and disposal, as more information about the technology becomes available. An assessment of regulatory barriers to these types of concrete would also be required to determine the size of the potential market for such products.

2.4 Circularity in the Dutch cement and concrete sector

There are several possible circular[3] options within the cement and concrete value chain. While the standard demolition process makes little room for reuse or recycling of concrete and its components, it is possible for end-of-life concrete components to be usefully recirculated in several ways, and a number of Dutch companies specialise in circular strategies for buildings and for cement and concrete in particular. The Dutch government also promotes a circular strategy; under the Rijksbrede programma Circulaire Economie, the cabinet has set targets of reducing the use of primary raw materials by 50% by 2030, and becoming fully circular by 2050 (Rijksoverheid, 2022).

Note that clinker substitution, though a high-potential and low-cost strategy for reducing cement and concrete-related emissions, is not considered to be a “circular” option, as the main available substitutes still require virgin extraction of raw materials, and do not link the final product (cement or concrete) back to its inputs.

1. *Regranulation of concrete into aggregate*
   This option entails grinding discarded concrete products (typically components of buildings, infrastructure, and roads that are recovered after demolition) into small pieces that can be subsequently used as “aggregate” – replacing some of the natural stone and mineral materials needed to produce concrete. This could reduce some emissions related to mining and quarrying, and grinding energy would still be required. This would not have an impact on the large share of emissions related to clinker calcination, as the same amount of clinker would be required for new cement and concrete. Recovered concrete material is currently used for low-value applications, such as building road foundations.

   TU Delft researchers have also developed a process for recovering sand and cement fine particles from ground concrete, via Advanced Dry Recovery (ADR) and Heating Air classification System (HAS). This process has been patented and is commercialised by C2CA at industrial scale. Currently the process is used to commercially produce recycled aggregates of a variety of size classes (Gebremariam, di Maio and Rem, 2020)(C2CA, 2022)(Wassink, 2017).

2. *Reuse of concrete*
   This option entails designing components that can be disassembled and reused at the end of the lifetime of a building or structure. For example, even if a building is replaced after 75 years, a well-maintained concrete slab may have a lifetime of 50 to 100 years – and for non-reinforced concrete, there are examples of much longer lifetimes. With the principle of “design for reuse,” these slabs could be removed and reused or repurposed in a new building or structure, reducing the need for new concrete (and thus cement and clinker). This would require a substantial change in how the construction sector currently operates, as demolition would become more complicated and expensive, as well as changes in regulation to allow for such reuse. However, it has the potential to save emissions at every previous step of the value chain. The Betonakkoord CO_2 Reduction Roadmap estimates a potential for 20

[3] Taken narrowly to mean recirculation of a product (or its components) to reduce discarded waste and virgin material extraction/production.

$ktCO_2$/year savings in 2030 based on reuse of concrete elements (Betonakkoord 2021).

Currently, reuse of concrete elements of buildings or structures is rare. Some studies of the practice have been carried out. The table below presents an assessment of current reuse of concrete-base products from housing in the Netherlands, as well as some important stimulating factors and barriers to increased reuse. In most cases, the lack of cost incentive and experience is the main reason that reuse is uncommon.

Material type group	Product	Availability in the market or reused building products in the Netherlands	Stimulating factors	Lifetime	Blocking factors
Products derived from housing deconstruction/ renovation (not new)					
Stony based materials: Concrete and natural stones	Staircase	Not common	Can be reused for landscape	100+ years [2]	Comparative low cost of new products.
	Structural pre cast concrete products (columns, beams, portal frames, floor planks)	Not common	Need more experiments with cascade reuse	100+ year [2]	Large size components have complex for deconstruction. No market demand. Cost to handle and equipment may be a barrier for cascading.
	Concrete floor tiles (external)	Less common	Easy for reuse	30 years [1]	Cheap price for new component.
	Concrete roof tiles	Not common	Need more experiments with cascade reuse	40-50 years [2]	Cheap price for new component. Although relatively common in post war housing projects, concrete roof tiles are generally not reclaimed in the country.
	Lintels	Not common	Need more experiments with cascade reuse	100+ years [2]	Comparative low cost of new products.

Source: Icibaci, 2019.

1. *Recovery of cement from concrete*
   The Rutte Groep, a Dutch construction company, in collaboration with New Horizon Urban Mining, a Dutch circular demolition company, is the first in the world to market recovered cement from used concrete, called “Freement.” The process involves rotating shafts that grind and separate the concrete into gravel, sand, and cement. The technology to process concrete back into cement is still at small scale (130 kt concrete per year capacity), and public information on the yield of the process is not available (Freement, 2018). For context, about 30 Mt (almost 13 million cubic metres) of concrete was used in the Netherlands in 2017 (CE Delft 2020). However, if this eventually scales up, it would have the potential to reduce a significant portion of emissions related to cement manufacturing. The publicly available data is currently insufficient for a lifecycle assessment.

   Eventually, the ADR and HAS process discussed above may also be used to produce ultrafine particles that can be used as a cement replacement. However, at present this application has not been applied commercially (Gebremariam, Maio and Rem, 2020).

2.5 Relevance of case studies

Lifecycle assessments will be most relevant for options with high potential for emission reductions, high potential for commercial application in the Netherlands, and sufficiently available data. A qualitative assessment of each potential case study on each of these three points follows below.

	Emission reduction	Potential applications in the Netherlands	Data availability
Carbon capture in the cement sector	High	Low	High
CO_2 -injection in ready-mix concrete	Medium	High	Medium
CO_2 -curing of precast concrete products	Medium	High	Medium
Regranulation of con-crete	Low	High	High
Reuse of concrete	High	Medium	Medium
Recovery of cement from concrete	High	High	Low
Alternative binders (incl. ASCEM)	Medium	High	Medium

Figure 20 Qualitative assessment of criteria for further investigation of case studies
Red = low reductions, potential or availability, Orange= medium, Green= high

Emission reductions

All of the examined circular and CCUS options for the cement and concrete sector have a reasonable scientific basis for potential emission reductions, though for the less broadly implemented and studied options – particularly novel alternative binders and CO_2 uptake via recarbonation of concrete products – there is still considerable uncertainty about these estimates. The specific application of these strategies will determine the exact magnitude of lifecycle emission reductions.

Potential applications in the Netherlands

As discussed, no clinker kilns are currently operational in the Netherlands, making carbon capture unlikely to play a role domestically. The other options examined all occur at the concrete production stage, end-of-life, or are alternative products that could be developed in the Netherlands to replace cement.

According to Material Economics, half of European cement consumption is used in the construction of new buildings, and 30% in the construction of infrastructure, with the remainder used for mainly for maintenance and repair work. The large majority of this cement is used in concrete, and of that, about half is used in ready-mix concrete (Material Economics, 2019). Values for the Netherlands should be investigated, and local relevance taken into account in the selection of case studies.

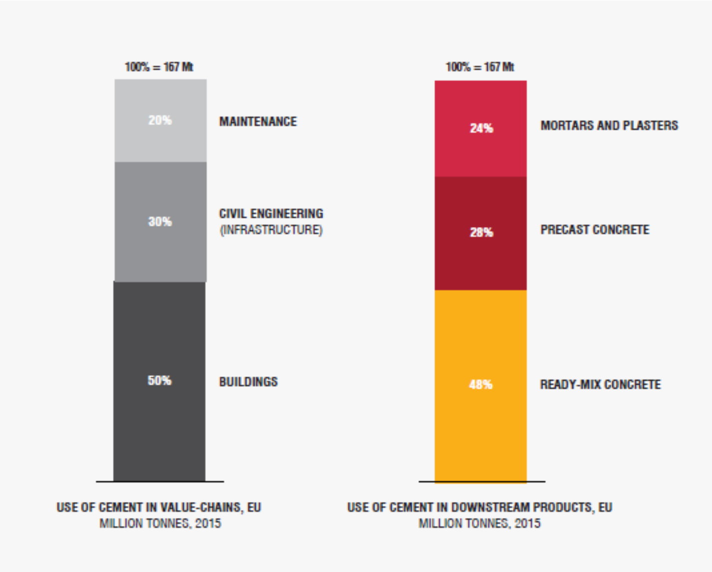

Figure 21 Cement use in the EU in 2015 (Material Economics, 2019)

Data availability

While publicly available data on industrial processes is often limited, public information about early-stage technologies, such as recovery of cement from concrete, is even more limited. Performing an LCA would require working with industrial companies to obtain the necessary data about the process. Data availability for recarbonation processes, alternative binders, and reuse of concrete may also present an issue.

Existing tools and resources

For stakeholders in the building materials sector, organizations like Carbon Leadership Forum[4] and the European Laboratory for Green Transformable Buildings (GTB LAB) in Heerlen[5], among many others, promote a lifecycle emissions-conscious approach to architecture, providing tools and promoting best practices. The Netherlands is already recognized as a world leader in the circular building space[6].

The Embodied Carbon in Construction Calculator (EC3) is an internationally developed tool that can be used to benchmark and assess building material-related embodied emissions (Building Transparency, 2022). The report “Carbon-based Design: Onderzoek naar de milieu-impact van de woningbouw,” from Rijksdienst voor Ondernemend Nederland (RVO), CityFörster architecture + urbanism, and Transitieteam Circulaire Bouweconomie, provides a theoretical basis and practical example of how to evaluate lifecycle emissions from residential buildings, including material-related emissions (CityFörster, RVO and Transitieteam Circulaire Bouweconomie, 2022).

CE Delft published a study in 2020 estimating the total climate impact of the use of concrete in the Dutch construction sector. The report was not an LCA, but did aim to quantify the climate impacts of raw materials for all the major cement and concrete types that are used

[4] https://carbonleadershipforum.org/who-we-are/
[5] https://www.gtb-lab.com/about
[6] For example, in this 2022 New York Times article: Aguirre, J.C. (2022), “How to Recycle a 14-Story Office Tower,” New York Times, 6 October 2022, https://www.nytimes.com/2022/10/06/headway/office-tower-carbon-emissions-amsterdam.html; and by the European Union: European Union (2019), “The Netherlands Adds A Circular Building Touch,” https://ec.europa.eu/environment/ecoap/about-eco-innovation/policies-matters/netherlands-adds-circular-building-touch_en

in the Netherlands for 1990, 2010 and 2017. The report already provides insights into the changes over the last two decades, and calls for additional research and better public data availability in order to improve the estimates (CE Delft 2022).

The Betonakkoord (Concrete Agreement), signed in 2018 by private and public sector stakeholders in the concrete value chain, sets out plans and roadmaps for meeting climate and circularity goals. Particularly relevant is the CO_2 Reduction Roadmap, published by the Betonakkoord stakeholders in 2021, describing potential contributions of different emission reduction strategies in order to meet 2030 targets of at least 30% reduction compared to 1990, and 100% carbon neutral operations in 2050 (Het Betonakkoord 2022)(Het Betonakkoord 2021). Many other resources are available internationally and in the Netherlands, aimed at stakeholders in manufacturing, design, construction, end-use and policymaking.

Given the specificities of each application of cement and concrete, project-specific LCA may in some cases be a more appropriate approach. Analysis of a specific building or infrastructure project allows the possibility of different materials used for load-bearing and non-load-bearing applications. These approaches can account not just for material use, but how material choice interacts with the use phase of the structure to impact emissions, for example from energy use in buildings or replacement of and maintenance of components.

3 Conclusions

Among the investigated options for reducing lifecycle emissions from the Dutch building materials sector, several value chains seemed like promising candidates for a lifecycle assessment. Several processes which promote CO_2 uptake in concrete, either via injection to ready-mix concrete or via CO_2 curing of precast concrete, are currently being scaled up and commercialised. Uncertainty remains about lifecycle emissions impacts, and the analysis of these cases would be valuable. Similarly, reuse and recycling of end-of-life concrete products could be – and in some cases, already is – applied in the Netherlands, and could reduce emissions both in the Netherlands and abroad. The use of alternative binders, such as ASCEM cement, while not fitting a strict definition of circularity, has potential reduce emissions as well, but should be balanced with the expected long-term availability of key raw materials. A preliminary qualitative assessment of the potential for emission reductions, amount of potential applications in the Netherlands, and data availability can provide some guidance on which value chains are most suitable for lifecycle assessment. Full lifecycle assessment would provide a better basis for policymaking regarding each of these identified value chains.

References

ADBRI (2022), "Clinker, concrete, cement, aggregate and masonry value chain," https://www.adbri.com.au/sustainability/sustainable-future/.

Aguirre, J.C. (2022), "How to Recycle a 14-Story Office Tower," New York Times, 6 October 2022, https://www.nytimes.com/2022/10/06/headway/office-tower-carbon-emissions-amsterdam.html.

Andrew, R. M. (2018), "Global CO_2 emissions from cement production," Earth Syst. Sci. Data, 10, 195–217, https://doi.org/10.5194/essd-10-195-2018, 2018.

ASCEM (2022), "Bindmiddeltechnologie," https://www.ascem.nl/nl/diensten/bindmiddeltechnologie/.

Betonakkoord (2022), "Het Betonakkoord nieuwe layout," https://www.betonakkoord.nl/.

Betonakkoord (2021), "Road Map CO_2 Reductie: Presentatie Stuurgroep," https://www.betonakkoord.nl/wp-content/uploads/sites/43/166796/road_map_co2_januari_2021_versie_1_2.pdf.

Betonhuis (2020), "Cementmarkt in Nederland," https://betonhuis.nl/cement/cementmarkt-nederland.

Buchwald, A. and Wiercx, J.A.L.M. (2012), "CO_2 optimized cement based on synthetic slag made of fly ash," Proceedings of the EUROCOALASH 2012 Conference, September 25-27, 2012, http://www.evipar.org/innet/files/EUROCOALASH2012/Docs/slides/036_Buchwald-Wiercx_-EUROCOALASH2012-paper.pdf.

Burgess, J. (2021), "Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route," S&P Global Commodity Insights, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/092121-dutch-ccs-project-scrapped-after-tata-steel-opts-for-hydrogen-dri-production-route.

Building Transparency (2022), "EC3 Resources," https://www.buildingtransparency.org/ec3-resources/.

Carbon Recycling International (2022), "The Shunli CO_2 -to-Methanol Plant: Commercial Scale Production in China," https://www.carbonrecycling.is/projects.

CarbonCure (2022a), "CarbonCure's 500 Megatonne CO_2 Reduction Technical Roadmap," http://go.carboncure.com/rs/328-NGP-286/images/CarbonCure%27s%20500%20Mt%20CO2%20Reduction%20Technical%20Roadmap%20eBook.pdf.

CarbonCure (2022b), "CarbonCure Concrete: A Permanent Storage Solution," https://www.carboncure.com/carbon-removal/carbon-removal-with-carboncure-concrete-a-permanent-solution/.

Carbon Smart (2022), "Materials Palette," https://materialspalette.org/concrete/.

CBS (2022a), "Population dynamics: month and year," https://opendata.cbs.nl/#/CBS/en/dataset/83474ENG/table?ts=1667215852341.

CBS (2022b), "Goederensoorten naar EU, niet-EU; minerale brandstoffen en chemie," https://www.cbs.nl/nl-nl/cijfers/detail/81261ned.

CE Delft (2020), "Klimaatimpact van betongebruik in de Nederlandse bouw: Vergelijking 1990, 2010 en 2017," https://ce.nl/wp-content/uploads/2022/09/CE_Delft_190417_Klimaatimpact_betongebruik_in_Nederlandse_bouw_DEF.pdf.

CE Delft (2013), "Milieu impact van betongebruik in de Nederlandse bouw: Status quo en toetsing van verbeteropties," https://cedelft.eu/wp-content/uploads/sites/2/2021/04/CE_Delft_2828_Milieu-impact_van_betongebruik_DEF_1380108994.pdf.

Cembureau (2022), "Cement," https://cembureau.eu/about-our-industry/cement/.

Cembreau (2021), "2021 Activity Report," https://cembureau.eu/media/03cgodyp/2021-activity-report.pdf.

CityFörster, RVO and Transitieteam Circulaire Bouweconomie (2022), *Carbon-Based Design: Onderzoek naar de milieu-impact van de woningbouw*, https://circulairebouweconomie.nl/wp-content/uploads/2021/10/Carbon-Based-Design.pdf.

CSI and ECRA (2017), "Technology Papers 2017: Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead," https://ecra-online.org/research/technology-papers/.

De Nederlandsche Bank (2022), "DNB bouwt met CO_2 -neutraal beton," https://www.dnb.nl/algemeen-nieuws/nieuwsbericht-2022/dnb-bouwt-met-co2-neutraal-beton/.

Edwards, P. (2022), "Bio-cement from algae," *Global Cement Magazine*, October 2022.

ENCI (2022), "ENCI Maastricht," https://www.enci.nl/nl/enci-maastricht#:~:text=ENCI%20Maastricht%2C%20de%20eerste%20productielocatie,aan%20de%20cementproductie%20in%20Maastricht.

European Union (2019), "The Netherlands Adds A Circular Building Touch," https://ec.europa.eu/environment/ecoap/about-eco-innovation/policies-matters/netherlands-adds-circular-building-touch_en.

Freement (2018), "Nederlandse primeur: circulair cement schudt betonsector op," https://freement.nl/nederlandse-primeur-circulair-cement-schudt-betonsector-op/.

Global Cement and Concrete Association (GCCA) (2022a), "Alternative binders," https://gccassociation.org/cement-and-concrete-innovation/alternative-binders/.

GCCA (2022b), "Carbon uptake, " https://gccassociation.org/sustainability-benefits-of-concrete/carbon-uptake/.

Gebremariam, A.T., di Maio, F., and Rem, P. (2020), "Innovative technologies for recycling End-of-Life concrete waste in the built environment," *Resources, Conservation and Recycling* 163:104911.

Global CCS Institute (2022), "CO2RE Database: Facility Data," https://co2re.co/FacilityData, accessed 21 November 2022.

Hanifa, M., et al. (2023), "A review on CO_2 capture and sequestration in the construction industry: Emerging approaches and commercialised technologies," *Journal of CO_2 Utilization* 67: 102292.

Icibaci, L. (2019), "Re-use of Building Products in the Netherlands: The development of a metabolism based assessment approach," *Architecture and the Built Environment*, TU Delft, https://journals.open.tudelft.nl/abe/article/view/3248.

IEA (2022a), *Cement*, IEA, Paris, https://www.iea.org/reports/cement.

IEA (2022b), *Global Energy Review: CO_2 Emissions in 2021*, https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

IEA (2019), *Material efficiency in clean energy transitions*, IEA, Paris, https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions.

IEA and CSI (2019), *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, IEA, Paris, https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

IEAGHG (2013), "Deployment of CCS in the Cement Industry," 2013/19, December, 2013, http://documents.ieaghg.org/index.php/s/oIBhweTvc1764Ih.

Katajisto, O. (2022), ,"Decarbonate: Cement precalcination with electricity and carbon dioxide sequestration," VTT, https://www.decarbonate.fi/wp-content/uploads/2022/05/2022-05-17-Betonitutkimusseminaari.pdf.

Keramidas, K., Mima, S., and Bidaud, A. (2021), "Pathways towards a net-zero carbon emissions cement: a modelling-based approach integrating demand and supply," CNRS, Université Grenoble-Alpes, and European Commission Joint Research Centre, https://hal.archives-ouvertes.fr/hal-03252093/file/20210607%20IAEE2021%20-%20Keramidas_Cement.pdf.

Keys, A., van Hout, M., and Daniëls, B. (2019), *Decarbonisation Options for the Dutch Steel Industry*, PBL and TNO, https://www.pbl.nl/en/publications/decarbonisation-options-for-the-dutch-steel-industry.

LEILAC (2022), "Leilac-2", https://www.leilac.com/project-leilac-2/.

Li, Z., He, Z., and Chen, X. (2019), "The Performance of Carbonation-Cured Concrete", *Materials*, 12 November 2019, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6888366/.

Material Economics (2019), *Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry*, https://materialeconomics.com/publications/industrial-transformation-2050.

Martinez, C.M., del Bosque, I. F. S., Medina, G., Frias, M., and de Rojas, M. I. S. (2021), "Fillers and additions from industrial waste for recycled aggregate concrete," *The Structural Integrity of Recycled Aggregate Concrete Produced with Fillers and Pozzolans*, Awoyera, P.O., Thomas, C., and Kirgiz, M.S., eds., Woodhead Publishing.

Monkman, S., and MacDonald, M. (2017), "On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete," *Journal of Cleaner Production*, 167: 365-375.

Nature (2021), "Concrete needs to lose its colossal carbon footprint," *Nature*, 597:593-594.

Nederlandse Emissieautoriteit (NEA) (2022), "Emissiecijfers over 2021," https://www.emissieautoriteit.nl/onderwerpen/rapportages-en-cijfers-eu-ets/documenten/publicatie/2022/04/14/emissiecijfers-2021.

Norcem (2022), "Carbon Capture and Storage (CCS): World first cement CCS-facility at Norcem Brevik in Norway," https://www.norcem.no/en/node/26363.

PBL and TNO (2022), "MIDDEN: the database,", PBL and TNO, https://www.pbl.nl/en/middenweb/the-database.

Ravikumar et al. (2021), "Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit," *Nature Communications* 2021, https://www.nature.com/articles/s41467-021-21148-w

Rijksdienst voor Ondernemend Nederland (RVO) (2019), "Erkende Maatregelenlijst Bouwmaterialen," https://www.rvo.nl/sites/default/files/2019/10/Erkende%20Maatregelenlijst%20Bouwmaterialen.pdf.

Rijksoverheid (2022), "Nederland circulair in 2050," https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050.

Scrivener, K., John, V.M., and Gartner, E. M. (2018), "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry," *Cement and Concrete Research* 114: 2-26.

Shao, Y., Mirza, M.S., and Wu, X. (2006) "CO_2 sequestration using calcium-silicate concrete," *Canadian Journal of Civil Engineering* 33:6.

Solidia Technologies (2022), "Solidia Technologies: Company Overview," https://assets.ctfassets.net/jv4d7wct8mc0/3WJE4m11HeTbucCjKKjqi2/4e9a0127316518576b617cd69b951f1d/Solidia_Technologies_Company_Overview_Backgrounder_11.27.19.pdf.

Steelanol (2022), "Steelanol recycles carbon into sustainable, advanced bio-ethanol," http://www.steelanol.eu/en.

Stripple, H., Ljungkrantz, C., Gustafsson, T., and Andersson, R. (2018), "CO_2 uptake in cement-containing products: Background and calculation models for IPCC implementation," https://www.ivl.se/download/18.72aeb1b0166c003cd0d64/1541160245484/B2309.pdf.

Tata Steel (2022a), "HIsarna: Building a sustainable steel industry," https://www.tatasteeleurope.com/sites/default/files/tata-steel-europe-factsheet-hisarna.pdf.

Tata Steel (2022b), "Together towards a zero-carbon emissions, circular world," https://www.tatasteeleurope.com/sustainability/green-steel-solutions/zeremis.

Tata Steel (2021), "Tata Steel opts for hydrogen route at its IJmuiden steelworks," https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks.

Wassink (2017), "The last step in concrete recycling," Delta, https://www.delta.tudelft.nl/article/last-step-concrete-recycling.

West, K. (2020), "HIsarna technology factsheet", https://energy.nl/data/hisarna/, TNO.

WorldSteel (2022), *World Steel in Figures 2022*, https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/.

Xavier, C., and Oliveira, C. (2021), *Decarbonisation Options for the Dutch Cement Industry*, PBL and TNO, https://www.pbl.nl/en/publications/decarbonisation-options-for-the-dutch-cement-industry.

Yearsley, B., and Lake, D. (2022), "OPUS: Make your own SCM," *Global Cement Magazine*, October 2022.

Glossary

Alternative binder – Alternative products with binding properties that can fully or partially replace Portland cement. These can be based on alternative chemistries or different processes, but can also rely on a similar chemical process.

Alkali-activated binder – Also known as geopolymers, alkali-activated materials are alternative binders based on the reaction of an alkali source and aluminosilicate, and sometimes based on industrial waste products such as metallurgical slags and coal fly ash.

Binder intensity – Binder intensity describes the amount of binder (clinker, or an alternative binder) required for a certain amount of compressive strength.

Blended cement – Cement with a lower share of clinker than Portland cement, due to substitution of alternative mineral components, such as gypsum, limestone, blast furnace slag, coal fly ash, and natural volcanic material. This corresponds to European standards for CEM II, III, IV and V.

Clinker – An intermediate product in cement manufacturing and the main component of cement, which gives it its hydraulic properties. The result of limestone calcination in a kiln and subsequent reactions.

Clinker ratio – Ratio of clinker content in the total cement (on a mass basis). Globally, this has fallen from about 0.95 on average in the 1970s to about 0.65 today (Andrew 2018).

Cement – A building material made by grinding clinker together with various mineral components, which acts as the binding agent when mixed with sand, gravel/crushed stone, and water to make concrete (or with water alone to make mortar).

Concrete – Material made up of cement, sand and gravel or other fine & coarse aggregate.

Ordinary Portland cement (OPC) – The most common type of cement, consisting of over 90% clinker and about 5% gypsum. This corresponds to CEM I in European standards.

Supplementary cementitious materials (SCMs) – Materials that contribute to the properties of concrete, when used in combination with Portland cement, through hydraulic or pozzolanic activity.

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