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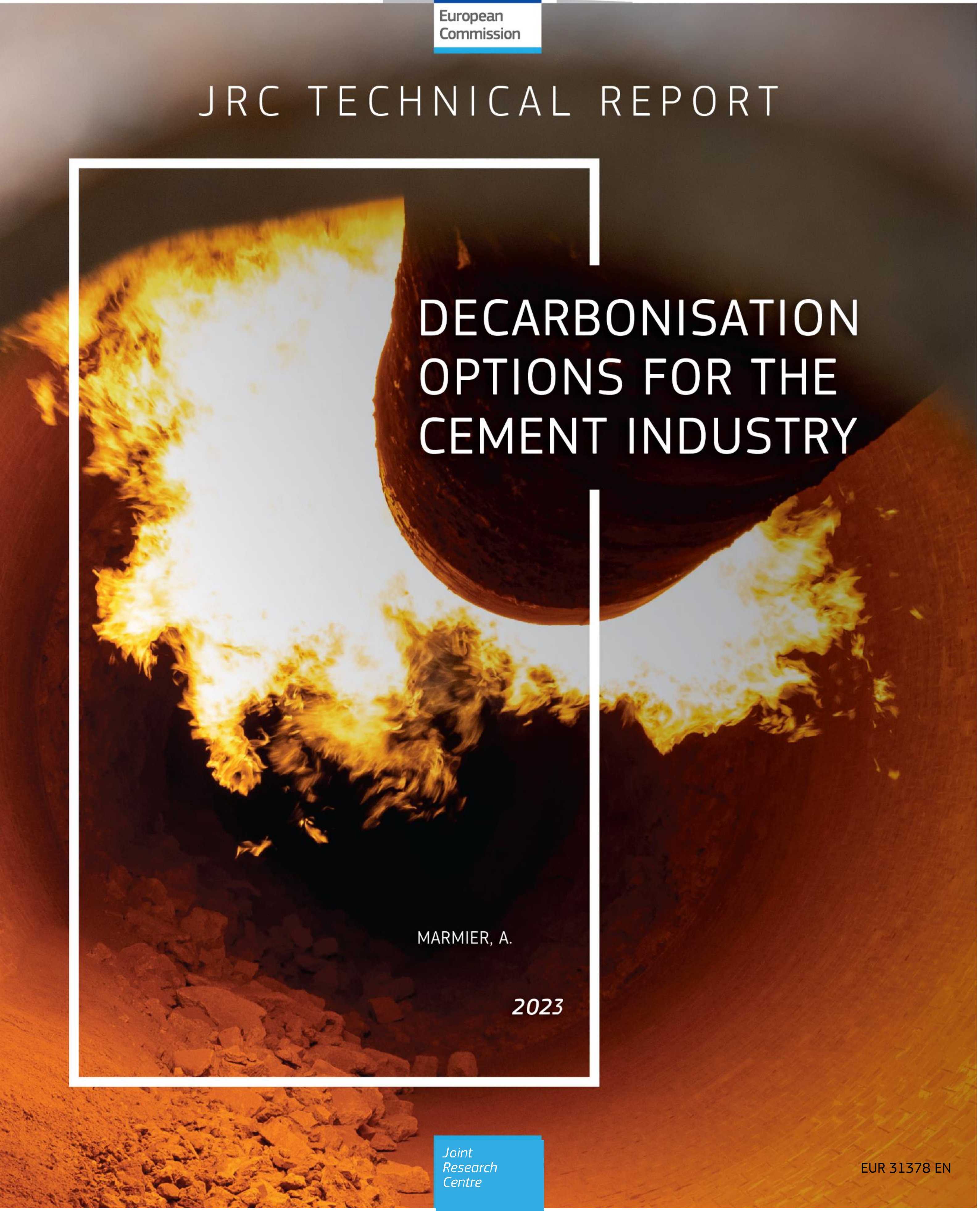

DECARBONISATION OPTIONS FOR THE CEMENT INDUSTRY

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Abstract

The cement industry is a building block of modern society, and currently responsible for around 7% of global and 4% of EU CO2 emissions. While facing global competition and a challenging business environment, the EU cement sector needs to decarbonise its production processes to comply with the EU's ambitious 2030 and 2050 climate targets. This report provides a snapshot of the current cement production landscape and discusses future technologies that are being explored by the sector to decarbonise its processes, describing the transformational change the industry faces. This report compiles the current projects and announcements to deploy breakthrough technologies, which do require high capital investments. However, with 2050 just one investment cycle away, the sector needs to commercialise new low-CO2 technologies this decade to avoid the risk of stranded assets. As Portland cement production is highly CO2-intensive and EU plants are already operating close to optimum efficiency, the industry appears to be focussing on carbon capture storage and utilisation technologies - while breakthroughs in alternative chemistries are still being explored - to reduce emissions. While the EU has played an important role in supporting early stage R&D for these technologies, it is now striving to fill the funding gap for the commercialisation of breakthrough technologies. The recent momentum towards CO2-free cement provides the EU with the opportunity to be a frontrunner in creating markets for green cement.

Executive summary

Cement is an industry poised to decarbonise its production process for the EU to reach carbon neutrality by 2050. The aim of this report is to take the stock of past and ongoing developments in the EU cement ecosystem, with a focus on technology development and alternative options towards decarbonisation. To this end, this report collects and makes sense of literature describing technologies and options applicable in the cement industry: roadmaps and technology pathways give directions that the industry is expected to follow; research projects provide snapshots of technology development; ongoing demonstration projects and investments by cement producers hint at closeness to commercialisation. Further (public and corporate) funding and pledges towards decarbonisation demonstrate joint ambitions in the transition of this energy and CO_2-intensive industry towards sustainability.

Policy context

The EU has set clear ambitions for decarbonisation, with a target to reduce GHG emissions by at least 55% by 2030, supported by the comprehensive Fit-for-55 legislation package, and the long-term objective to become the first climate-neutral continent by 2050, set out in the European Green Deal policy initiatives and anchored by the European Climate Law. In order to reach these goals, EU industry, including the cement sector, will need to transform its current highly CO_2-intensive processes.

Besides policies aimed at decreasing pollution or at improving energy efficiency and competitiveness, the EU climate policy is a key driver of innovation. Its main instrument, the EU Emissions Trading System (ETS), aims to constrain CO_2 emissions within the EU. The Carbon Border Adjustment Mechanism (CBAM) will complement the ETS by equalising the carbon cost of imported goods into the EU with the carbon costs incurred in the EU under the ETS. CBAM makes free allocations under the ETS unnecessary, and thus reinforces the impact of the ETS's CO_2 capping and price. Lastly, incomes generated by the ETS will be geared towards compensating for the incurred costs: the innovation fund, one of the world's largest funding programmes, is expected to stimulate innovation in low carbon technologies by supporting the demonstration of decarbonisation technologies.

Main findings

Emissions of the cement industry are linked to the current production process: in the EU, about 60% of cement emissions stem from the calcination of limestone into calcium oxide; about 30% stem from the need for heat to power thermal processes; and the rest (approx. 10%) are emissions linked to electricity consumption. This observation provides avenues for addressing emissions, now and in the future, building on ongoing trends:

- Linked to fuel prices, several options aiming at process efficiency are already largely deployed: efficient kiln technology is now the norm, challenging the case for waste heat recovery;
- Emissions linked to the production of calcium oxide are the new focal point, with ongoing efforts aimed at reducing CaO content in cement or at sourcing oxides in less CO_2-intensive ways;
- With the potential of addressing all CO_2 emissions irrespective of their origins, carbon capture, utilisation and storage (CCUS) is now gaining momentum, with research funding and demonstration projects multiplying.

Key conclusions

In the absence of a single dominant technology for the decarbonisation of the cement industry, all options remain of importance. This is especially true of the cement industry, which is local in nature, and for which solutions may well be site-dependent. Hence the need for the present study, examining the trends, research and technology developments of the industry.

Related and future JRC work

Publication JRC120570, ‘Deep decarbonisation of industry: The cement sector’, analysed decarbonisation scenarios affecting the cement industry towards 2050. While carbon capture and storage is deemed unavoidable for deep decarbonisation due to the process emissions inherent to cement making, other decarbonisation options (e.g. electrification, higher use of biomass, circularity) are nonetheless expected to contribute to the decarbonisation ambition of the cement industry with their mitigation potential.

Detailed analysis of pledges by EU cement manufacturers and of their announcements for upcoming facilities for the production of decarbonised cement will provide an updated and refined prospect on technologies that are close to the market. The techno-economic impact of these relevant technologies (regarding decarbonisation, cement price and EU competitiveness) will be key in determining the scale of their future deployment and the manner in which the EU cement industry will contribute to the overarching decarbonisation objectives of the EU.

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1 Introduction

The cement industry is key to the EU economy, producing a material that is crucial to EU's construction sector. However, the industry is also a major CO_2 emitter, responsible for some 4% of the EU's total CO_2 emissions. These emissions are inherent to the cement production process and hard to abate. The EU has enshrined ambitious targets to reduce emissions by 55% by 2030 and to become the first climate-neutral continent by 2050 in the European Climate Law [European Commission, 2021f]. This gives the sector the difficult task of aligning its production with the EU's climate targets while remaining competitive in a challenging global business environment.

Portland cement represents over 80% of EU27 cement production [European Commission, 2018]. It is currently made by calcining limestone (calcium carbonates) and sintering the resulting calcium oxide at high temperature with silicates from clay and quartz; the resulting clinker is then ground with additives producing a fine and reactive powder principally made of calcium silicates. CO_2 emissions are an inevitable product of this process. Integrated cement plants combine mills and dryers for raw material pre-processing, kilns for thermal processes (calcination and sintering), coolers and mills for the post-processing of clinker. These components operate in highly optimised and interconnected energy and materials streams. EU integrated plants are already among the most efficient worldwide, operating close to optimal thermodynamic levels, and there is little scope to reduce further CO_2 emissions.

A number of studies, from the private sector and institutional organisations [Agora Energiewende and Wuppertal Institute, 2021; Cembureau, 2020c; Chatham House, 2018; ECRA, 2016; ECRA & WBCSD/CSI, 2017; ETC, 2018; ISAL, 2021; ETH, 2018; IEA & WBCSD-CSI, 2018; NewClimate, 2020], have shown that fundamental changes are necessary to the cement production process, through breakthrough technologies, if emissions are to be brought in line with the 2050 greenhouse gases (GHG) reduction target. This involves changes in the cement industry's production processes and an increased sense of urgency. Due to the cement industry's long-lasting capital assets, 2050 is just one investment cycle away. Investment decisions made in the next decade will need to be aligned with the EU's climate targets if the industry is to avoid the risk of stranded assets or locking in CO_2 emissions beyond 2050. This need for action is reflected not only in the European Commission's update to the 2020 Industrial Strategy [European Commission, 2021a] but also in assessments by the cement industry [Cembureau, 2020c].

This report provides a snapshot of the current status of the cement sector and presents the main (technological) options that are being developed by EU cement producers to decarbonise cement production. While the European industry already largely optimised the thermal efficiency of its production process and is currently striving to diversify its sourcing of energy favouring carbon-neutral bioenergy, Carbon Capture, Utilisation and Storage (CCUS) is emerging as a viable option for addressing the industry's emissions. Significant investments are being made to push technological development towards demonstration phase. Further, research is ongoing for developing alternatives to the current industry standard. Efforts are ongoing towards the production of Portland cement with alternative routes and towards the production of alternatives to Portland cement. These two approaches do see investments coming-in.

This report also summarizes the financial support mobilised by the EU towards the cement industry: In addition to established funding for R&D projects, innovation fund and projects of common interest provide the means for pilot and demonstration projects.

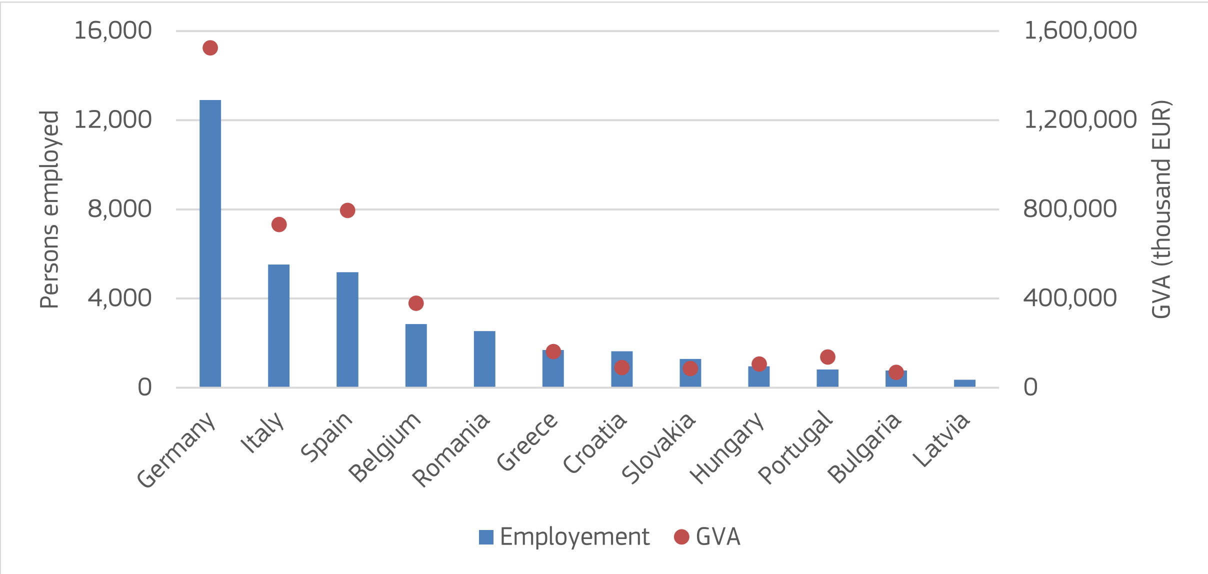
2 The cement decarbonisation challenge

Cement is an important material, both for today's society and for tomorrow's low-carbon economy. However, the European cement industry has been struggling in the face of rising global capacity, decreasing internal demand and most recently, a global pandemic and surging fuel prices. At the same time, deep reductions of emissions are needed from a sector that is one of the biggest industrial emitters of CO_2. The EU's policies have in the past not been sufficient to incentivise deep decarbonisation of the industry. However, recent policy momentum in the EU (EU's Industrial Strategy [European Commission, 2020b] and its update [European Commission, 2021a]) has put the spotlight on energy intensive industries, which are poised to further incorporate low-CO_2 technologies.

2.1 Cement's importance in the EU economy

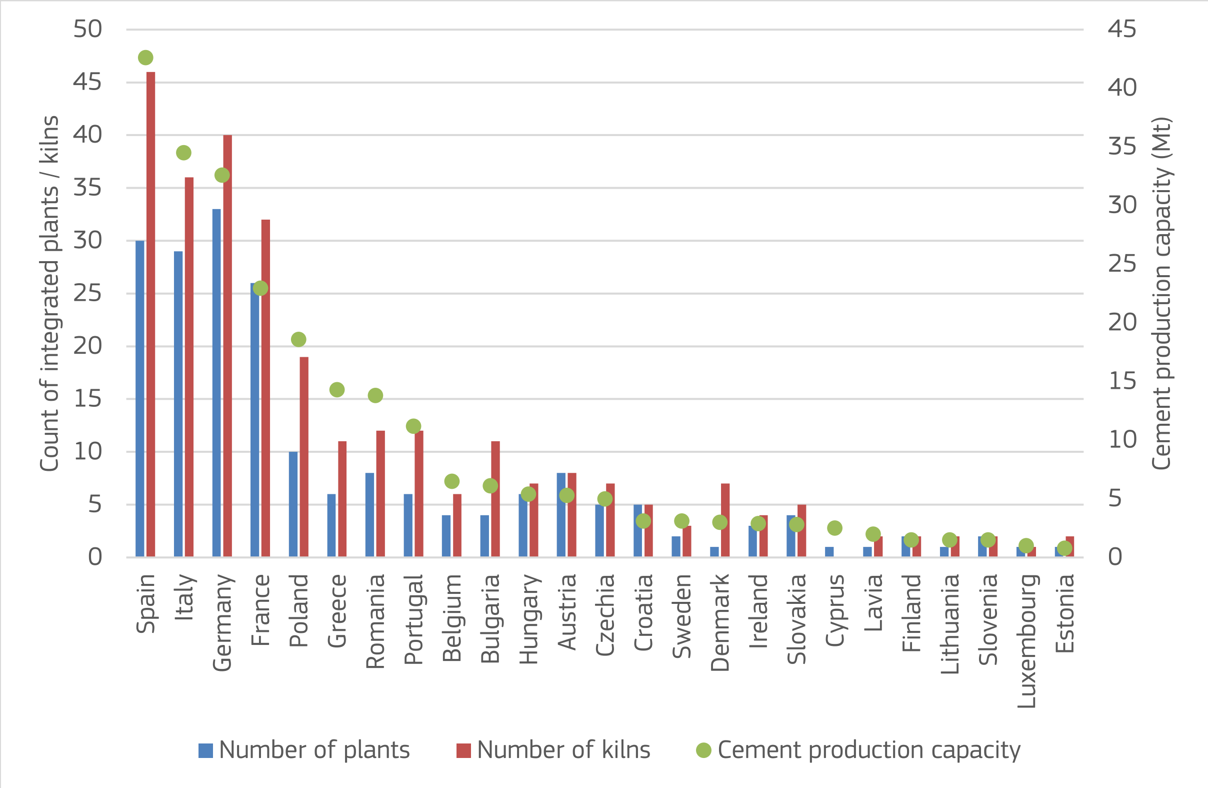
The European cement industry underpins a significant share of the EU economy. According to Eurostat, the sector directly employed over 36 000 people and created some EUR 4 billion of direct Gross Value Added (GVA) in EU27 in 2019 [Eurostat, 2021] or 35 176 people in EU28 in 2020 [Cembureau, 2020]. Taking into account the indirect impact of the industry through the activities supported by the sector's EU supply chains, the cement sector can be linked to a further 13 million jobs and 10% of EU's Gross Domestic Product [Cembureau, 2020c]. The cement sector has a footprint in many Member States, via the cement-producing sites and its downstream value chains.

Figure 1 cement sector (NACE 24.1) direct employment and Gross Value Added (GVA) per EU Member State, 2018



Source: JRC based on Eurostat

Figure 2 Number of cement integrated plants, kilns and production across EU Member State, 2022



Source: JRC based on [GCD, 2022]

Cement is a particularly important material, as it serves as cornerstone of the construction sector, which then underpins or includes other sectors of the EU economy, be it real-estate, transportation and energy. The sector has, however, struggled in recent decades, suffering a permanent demand drop after the 2008 financial crisis, with origins from the real-estate market. Further, cement trade across the EU27 borders has been gaining prominence over the last decades, with both imports and exports reaching over 10% of the EU27 production. It is **worth noting that, while variations in imports and exports of cement seem to be happening simultaneously, trades of clinker – main constituent of cement - do not follow a similar pattern (i.e. imports steadily decreased while exports increased)**: The EU27 went, in 2009 following the 2008 crisis, from being a net importer to being a net exporter of clinker, under the drive of the Spanish market: Spanish clinker exports benefited from overcapacity following the contraction of the national construction sector and from the location of the clinker production capacity, mainly close to the coastline [European Commission, 2018].

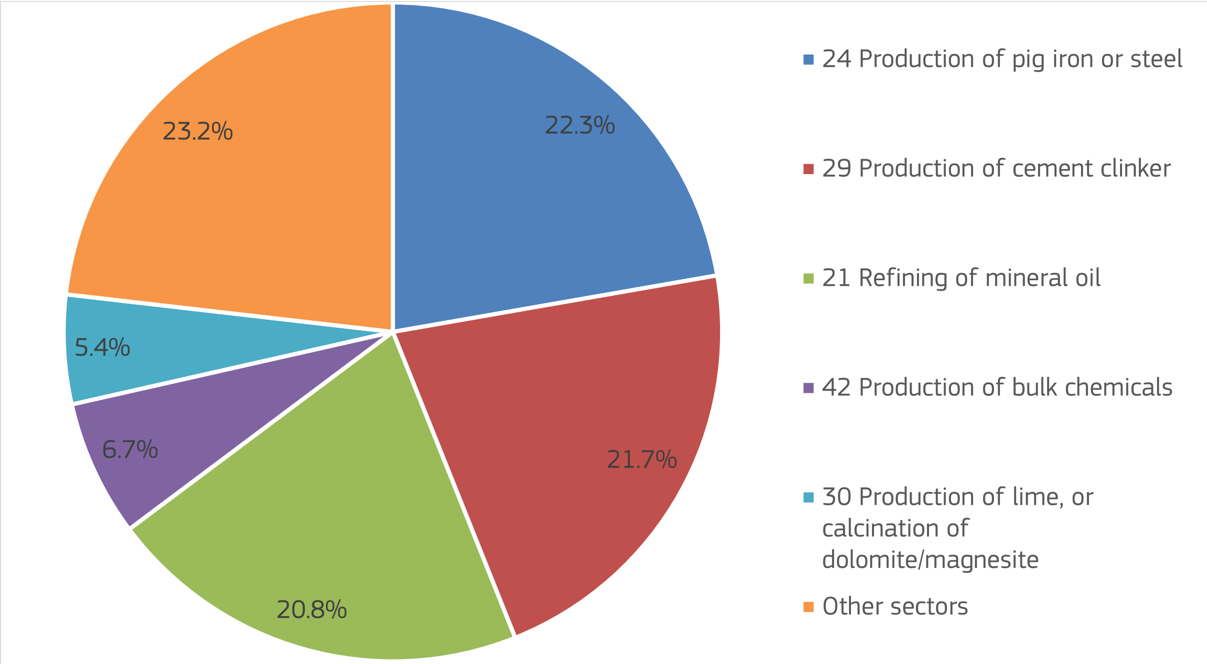
This latter aspect, i.e. the location of the cement plants, affects the cost of transport of cement from the plant to its customer [European Commission, 2013b]. Yet the overall cost of cement includes other components [European Commission, 2018]: (i) raw material (including transport), (ii) energy, (iii) maintenance and (iv) labour and other costs. This latter point covers e.g. insurance, overhead [Moya Rivera & Boulamanti, 2016]; 'operating surplus' (or profits), which can be derived from Eurostat SBS data for European countries; operational and capital costs [Rootzén & Johnsson, 2017]; and the price of CO_2, discussed below. While no study looks exhaustively into the competitiveness of the EU cement industry in comparison to the rest of the world, some components of the cost of cement, such as labour, are not in favour of European plants [Moya Rivera & Boulamanti, 2016].

This challenge in competitiveness is a drive towards innovation which then also supports other policy goals such as environmental sustainability, energy security and resilience.

2.2 The climate and environmental urgency

The cement industry is one of the biggest industrial emitters of CO_2. Globally, the sector is responsible for around 2.5 $GtCO_2$ emissions in 2020 [GCCA, 2021], or 7.1% of the 35 Gt global CO_2 emissions that year [Global Carbon Project, 2022]. In the EU27, the cement production led to 110 $MtCO_2$ emissions, 8.2% of all the emissions reported through the ETS [European Environmental Agency, 2022] and about 4% of all of the EU27 CO_2 emissions. Together with the iron and steel sector, the cement sector has the highest total CO_2 emissions of all energy-intensive industries.

Figure 3 Share (%) of verified emissions in EU27 industry sectors in t CO_2 equivalent reported under ETS, 2021



Source: JRC based on [EEA, 2022]

A significant share of these emissions are currently inherent to the way cement is made, with the calcination of limestone for clinker production, releasing CO_2 in the process. Besides these (process) emissions, the high temperatures required for the thermal processes are the result of fuel combustion, also prone to CO_2 emissions. Since fuel accounts for a high share of cement cost, a large majority of European plants already transitioned from wet towards dry processes (**Figure 27**), thereby improving on efficiency and emissions. Yet, several technical options for further incremental efficiency improvement and thus decarbonisation option remain [European Commission, 2013b]. Achieving the deep CO_2 emission reductions necessary will require major changes to the industry to deploy new low-CO_2 technologies, including carbon capture and storage, as well as circular economy solutions [European Commission, 2021e]. The urgency of this transition is reinforced by the long investment cycles of cement making assets. Cement kilns, the cornerstone of integrated cement making plants, have operating lives of up to 60 years [Agora Energiewende and Wuppertal Institute, 2021]. If reinvestment is made in existing infrastructure at the end of its technical life, there is an accrued risk of locking in CO_2

emissions, missing out on CO_2 infrastructures for carbon capture or even stranding assets. For the cement industry to successfully transition towards net-zero by 2050, decisions on investments will need to be made in the next decade and will need to be aligned with the strategies to decarbonise the sector. Estimates calculate that by 2030, about 30% of today's cement production plants will reach the end of their lifetimes [Agora Energiewende and Wuppertal Institute, 2021]. Reinvestments into the current CO_2-intensive production pathway risks locking in emissions until 2050 and beyond, or creating future stranded assets.

2.3 The policy context

The EU has set clear ambitions for decarbonisation, with a target to reduce GHG emissions by at least 55% by 2030, supported by the comprehensive Fit for 55 legislation package, and the long-term objective to become the first climate-neutral continent by 2050, set out in the European Green Deal policy initiatives and anchored by the European Climate Law [European Parliament and Council of the EU, 2021]. For these goals to be reached, the EU's industry, including the cement sector, will need to transform its current highly CO_2-intensive processes. The Commission's 2020 Industrial Strategy and its 2021 update highlights the need to further accelerate the green and digital transition of Europe's industry and increase the resilience of EU industrial ecosystems. Building on the High-Level Group on Energy-Intensive Industries "Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050" [HLG EII, 2019], several actions have been launched to accelerate the transformation of EU industries. These include the European Research Alliance (ERA) Common Industrial Technologies Roadmaps, launched in 2020 in the New ERA Strategy [European Commission, 2020d]; and the co-creation of a transition pathway for the energy-intensive industries ecosystem, in partnership with industry, public authorities, social partners and other stakeholders, [European Commission, 2021d]. One of these roadmap, the Industrial Technology Roadmap for Low Carbon Technologies in Energy-Intensive Industry, identifies technological options for the decarbonisation of industries and the means for their prioritisation, for their support and for their prompt implementation [European Commission, 2022a]. This endeavour is especially important for the cement industry, in which companies show a low R&D intensity [Grassano et al., 2022].].

Besides Research and Development, aimed at technological innovation and competitiveness, other policies are at play in the cement industry [European Commission, 2018]: A key policy mechanism for reducing industry's emissions is the EU Emissions Trading System (ETS). As a consequence of the EU's increased emissions reduction ambition, the emissions reduction target for ETS sectors, including the cement industry, has increased to 61% by 2030 vs 2005 in the proposed revision of the ETS directive [European Commission, 2021b]. Historically, the cement sector and other energy-intensive industries have been shielded from the full carbon price in the ETS via free allocation of emission allowances. While this has effectively protected the industry from carbon leakage risks, it reduced the incentive, introduced by the carbon pricing, for a transition to climate-neutral technologies [Stede et al., 2021].

Investments in low-carbon technologies have in the past been further economically disincentivised by the low and volatile carbon price in the ETS. The average price in 2020 of 25 EUR/tCO_2 [ICAP, 2021] was still far below the current indicative breakeven costs of zero-carbon technologies [Sartor & Bataille, 2019]. In 2022, however, ETS prices have soared, climbing close to 100 €/tCO_2 in August (i.e. reaching the same order of magnitude than the cost of cement without carbon pricing). The free allocation of allowances currently means that CO_2 emitters are facing a much lower effective carbon rate and are still largely shielded from this surge in CO_2 prices, weakening the price signal that would incentivise investments in deep CO_2 reduction measures.

Figure 4 EU ETS price

Source: JRC based on [Ember, 2022]

As an alternative measure to mitigate carbon leakage risks, the Commission has proposed the introduction of a Carbon Border Adjustment Mechanism (CBAM) on the carbon content of imports [European Commission, 2021c]. This would ensure that exporters to the EU face the same carbon prices as EU industry is subject to under the ETS. As the CBAM is considered an alternative to free allocations, free allowances would be phased out gradually, while the CBAM is phased in. The cement sector is one of the selected industrial sectors, which also includes refineries, iron and steel, organic basic chemicals and fertilisers that will fall under the initial CBAM scope. Addressing free allocations in this way could incentivise investments into low-CO_2 production processes by integrating the carbon cost into the production cost of products.

In order to boost EU resilience through enhanced security of energy supply, the REPowerEU plan draws ambitious actions affecting energy-intensive industries. As all energy-intensive industries, the cement industry depends on large quantities of fuel. Yet 2022 saw political tensions at Europe's eastern borders and – subsequently – perturbations on the trade of (fossil) fuels and the increase of their prices. This drove the adoption of the REPowerEU plan, aiming at increasing energy security of supply and storage. The plan strives to save energy, diversify supplies, quickly substitute fossil fuels and smartly combine investments and reforms. It consequently stimulates decarbonisation options, beyond the "Fit for 55" package: Energy efficiency, fuel substitution, electrification, and an enhanced uptake of renewable hydrogen, biogas and biomethane by industry could save up to 35 billion cubic metres (bcm) of natural gas by 2030 on top of what is foreseen under the "Fit for 55" proposals. [European Commission, 2022b]. More in detail and still in comparison with the "Fit for 55" package, the "Non-metallic minerals" sector, which includes the cement industry, is foreseen to see a reduction of 7.8 bcm in the consumption of natural gas, partly compensated by increases in oil (1.05 bcm) and coal (0.77 bcm) consumption. This will be achieved by a reduction of 7 Million tonnes of oil equivalent (Mtoe) in energy consumption in industry, complemented by an increase in Renewable Energy Sources (RES) and hydrogen use, also in industry. [European Commission, 2022c]. **Worth noting that the EU27 cement industry hardly relies on natural gas, while coal represents 18% of its fuel for thermal energy** [GCCA, 2019, also developed in section 4.2]. The cement industry contribution to the foreseen reduction in natural gas in the "Non-metallic minerals" sector is likely to remain marginal.

Further, the 2010 Industrial Emission Directive strives to protect human health and the environment from harmful industrial emissions across the EU. In order to reduce industrial emissions, the European Commission issues, as Implementing Decisions, the Best Available Techniques (BAT) in certain industries and the associated environmental performance of these techniques. These values then become the references for setting permit conditions of industrial facilities. In the case of cement, the Best Available Techniques Reference Document (BREF) and its conclusions were issued in 2013 [European Commission, 2013; European Commission, 2013b].

3 The cement sector today

To understand the decarbonisation challenges faced by the European cement industry, it is first important to understand how cement is currently made, both in the EU and globally. Cement is a mix of clinker and additives which serves as a binder. Clinker is the principal reactant while additives, historically in limited quantities, enhance cement characteristics. Clinker is the result of several thermal processes, including the calcination of limestone. This chemical reaction decomposes limestone calcium carbonates, thereby releasing significant and inevitable amount of CO_2. Other CO_2 emissions are the result of the combustion of fuels for powering the thermal processes. About 90% of EU cement plants already rely on the efficient dry thermal processes, making the scope for further CO_2 emission reductions limited.

3.1 How cement is currently made

Cement is a binder which, when it sets/hardens, aggregates and locks sand (eventually with stones) in a solid structure (i.e. mortar or concrete). Cement can be hydraulic (i.e. hardening and gaining strength when mixed with water) or non-hydraulic (i.e. hardening through other processes, such as carbonation with carbon dioxide). Due to restrictions in casting (i.e. slow hardening) and use (i.e. dry environment) the latter remains marginal and is not discussed in this report.

Among the hydraulic cements, three types are currently standardised in Europe:

— [EN 197-1, 2011] and [EN 197-5, 2021] provide specifications for (27 + five distinct) common cements. Depending on their Portland clinker content and additives (Blast furnace slag, Silica fume, Pozzolana, Fly ash, Burnt shale, Limestone), cements can be classified into:
  - CEM I Portland cement, with at least 95% clinker;
  - CEM II Portland-composite cement, of which between 65 and 94% weight is made of clinker;
  - CEM III Blast furnace cement, with between 5 to 64% weight in clinker;
  - CEM IV Pozzolanic cement, with between 45 to 89% weight in clinker;
  - CEM V Composite cement, with between 20 to 64% weight in clinker.

— [EN 14647, 2005] refers to calcium aluminate cements or aluminous cements, composed almost exclusively of calcium aluminate clinker;

— [EN 15743, 2015] is about supersulfated cements (SSC), which may contain up to 5% of Portland clinker and at least 75% of Granulated blast furnace slag.

The standards provide details on the composition of the various cements. As indicated above, all cements rely on clinker, though in different proportions: from about 5% of Portland clinker for supersulfated cements to more than 99.8% of calcium aluminate clinker for calcium aluminate cements. The clinker composition also varies: Portland clinker contains at least two-thirds by mass of calcium silicates ($3CaO{\cdot}SiO_2$ and $2CaO{\cdot}SiO_2$) [EN 197-1, 2011; EN 15743, 2015], while calcium aluminate cement contains between 35% and 58% of alumina and monocalcium aluminate is the main phase [EN 14647, 2005].

While the production of Portland clinker and Portland cement is well documented, information related to calcium aluminate cement is scarce, supporting the idea of a small market as per the trades of this product (**Figure 14**). Depending on the purity of calcium aluminate expected, production may take place through sintering in a kiln, similarly to

Portland clinker, or through fusion [Stinnessen et al., (n.d.); USITC, 1994; Zapata et al., 2022].

Table 1 Overview of EU facilities producing calcium aluminate cements

Country	Company	Plant	Presence of kiln	Standardised along EN 14647
Croatia	Calucem (Cementos Molins) (1)	Pula		Yes
France	Imerys (2)	Dunkerque		Yes
France	Imerys (3)	Fos-sur-mer		Yes
Netherlands	Almatis (4)	Botlek		
Poland	Gorka (Mapei) (5)	Trzebinia	Yes	Yes
Spain	Cementos Molins (6)	Sant Vincenç dels Horts Plant	Yes	Yes

(1) https://calucem.com/products/istra-types/ and https://calucem.com/products/lumnite-refcon/
(2) https://www.imerys.com/public/2022-03/imerys-business-documentation-declaration-of-performance-ciment-fondu-dk-14-january-2022.pdf
(3) https://www.imerys.com/public/2022-03/imerys-business-documentation-declaration-des-performances-ciment-fondu-fos-14-janvier-2022.pdf
(4) https://www.almatis.com/about/our-production-facilities/#Rotterdam,%20The%20Netherlands%20(Almatis%20B.V.) and https://www.almatis.com/media/swnhajyv/gp-rcp_005_cac_0516.pdf
(5) http://www.gorka.com.pl/pdf/en/g40_cert_en.pdf
(6) https://www.cmi.cemolins.es/uploads/media//E1-CMI/5201_Fichas-de-producto/Electroland/Ficha-Producto/Ficha_producto_ELECTROLAND_ES.pdf

Source: JRC based on company announcements

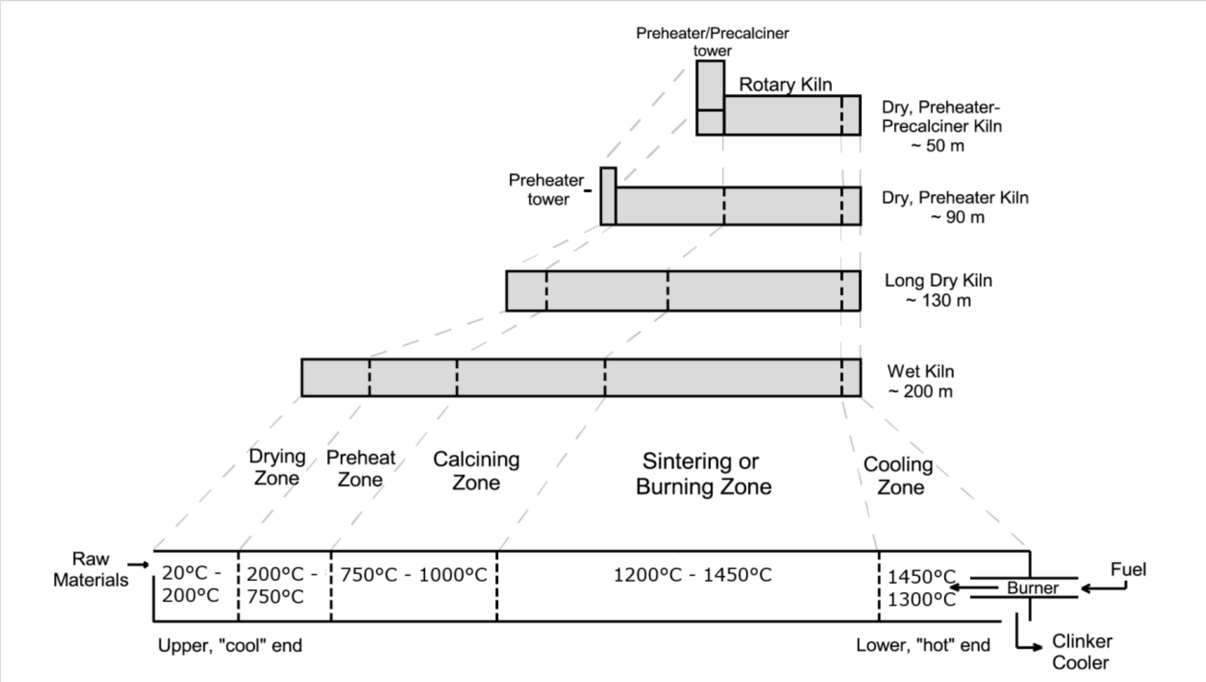
Regarding Portland clinker, calcium silicates (alite and belite, major phases) and calcium aluminates (tricalcium aluminate, and tetracalcium aluminoferrite, minor phases) are the result of the calcination of calcium carbonates into calcium oxide and its subsequent sintering with a source of alumina-silicate, such as clays. These processes and clinker production take place in an oven, called kiln, within a plant called “integrated”. “Integrated” plants extend the production of clinker with the production of cement through the grinding of cement constituents (clinker, additives and substitutes to clinker).

Large quantities of limestone are needed to produce the (intermediate) calcium oxide and then the cementitious phases. Integrated plants are then located close to limestone quarries, to minimise the cost of transport of this prominent raw material [European Commission, 2013b]. Limestone and other raw materials [quartz (SiO_2), clay minerals (SiO_2-Al_2O_3-H_2O) and iron oxide (Fe_2O_3)] are then crushed and ground finely. Once ground, the raw materials are dried and preheated to reduce their water content. Activation of the silicates through the removal of water and changes in the crystal structure takes place up to a temperature of about 700°C. Calcination, decomposing limestone’s calcium carbonates in calcium oxide, and the initial combination of the alumina, ferric oxide and activated silica with lime take place within the temperature range between 700 and 900°C. Calcium oxide, alumina silicates and silicon oxide are then sintered at high temperature in a cement kiln, thereby producing clinker: From 900 to 1200°C, belite forms. Above 1250°C and more particularly above 1300°C, the liquid phase appears and this promotes the reaction between belite and free lime to form alite. The cooling of clinker serves the purposes of fixing the mineralogical composition of clinker and pre-heating the air needed for the fuel combustion in the kiln. In integrated plants, the cooled clinker is then ground with gypsum to form Ordinary Portland Cement (OPC) and/or with other minerals for producing other types of cement (such as CEM II to CEM V). However clinker can also be transported to other locations, closer to customers, where only this grinding step will take place.

Technology evolved over the years, yielding to different architectures for the above mentioned steps (heating, calcination, sintering and cooling). In all cases, **the sintering** of raw materials at high temperatures, with materials reaching around 1450°C, takes place in rotating furnaces (kilns): Kilns are made of steel lined with refractory brick (allowing for the combustion gases to reach 2000°C), have a horizontal layout with a slight slope (2.5 to 4%) and turn at about 0.5 to 5.0 revolutions per minute. Clinker produced through this sintering is then **air-cooled**. Different cooler geometry are available, best described by the movement of clinker through the cooling process: Rotating coolers operate like kilns, mixing clinker and air through a spiralling motion; grate coolers move clinker horizontally while air flows vertically through the layer of clinker; vertical coolers let clinker fall through a heat exchanger while air flows in horizontal pipes.

Initially, the **drying** (depending on raw materials used), **preheating** and **calcination** steps also took place in wet or long dry rotary kilns. This allows removing humidity in raw meal (materials fed into the kiln) and raising raw meal temperature for thermal reactions, such as calcination, to take place, with the double effect of cooling down exhaust gases. For efficiency purposes (see **Table 2** below) these architectures tend to disappear. A more efficient way to recover the heat of the combustion gases implies a preheater tower, consisting of a series of vertical cyclone chambers. Before each chamber, hot gases are mixed with cold clinker. Both swirl through the cyclone chamber, efficiently exchanging heat. While the (cooler) gas exits at the top of the cyclone chamber, the (warmer) clinker exits at the bottom. The process repeats itself with gases cooling down as they go up and clinker heating-up as it goes down. Such "counter" flow motion allows for the drying of raw materials in top cyclones and its pre-heating in the bottom ones. With kiln exhaust gases reaching 1100°C, raw meal temperature increases up to 850°C. At this temperature raw meals calcium carbonates is already partially calcined. The addition of a combustion chamber between the preheater tower and the kiln (a pre-calciner) increases raw meal's calcination rate, further shortening the length of the kiln and increasing production rate.

Figure 5 Rotary kiln technologies and functional zones



Source: JRC based on [Van Oss & Padovani, 2008]

Table 2 Specific thermal energy demand by technology

Technology	**Specific thermal energy demand**	
	MJ/t clinker (1)	**Weighted average MJ/t clinker (2)**
Dry kiln with preheater and pre-calciner	3 000 < 4 000	3 515
Dry kiln with preheater without pre-calciner	3 100 to 4 200	3 700
Semi-wet/semi dry process	3 300 to 5 400	3 918
Dry kiln without preheater (long dry kiln)	Up to 5 000	3 570 (3)
Wet process	5 000 to 6 400	5 512
Shaft kilns	3 100 to 6 500 and higher	n.a.

(3) Excluding the energy needed for drying the fuels

Source: JRC based on (1) [European Commission, 2013b] & (2) [GCCA, 2019]

3.2 Where cement is made – in the world and in the EU

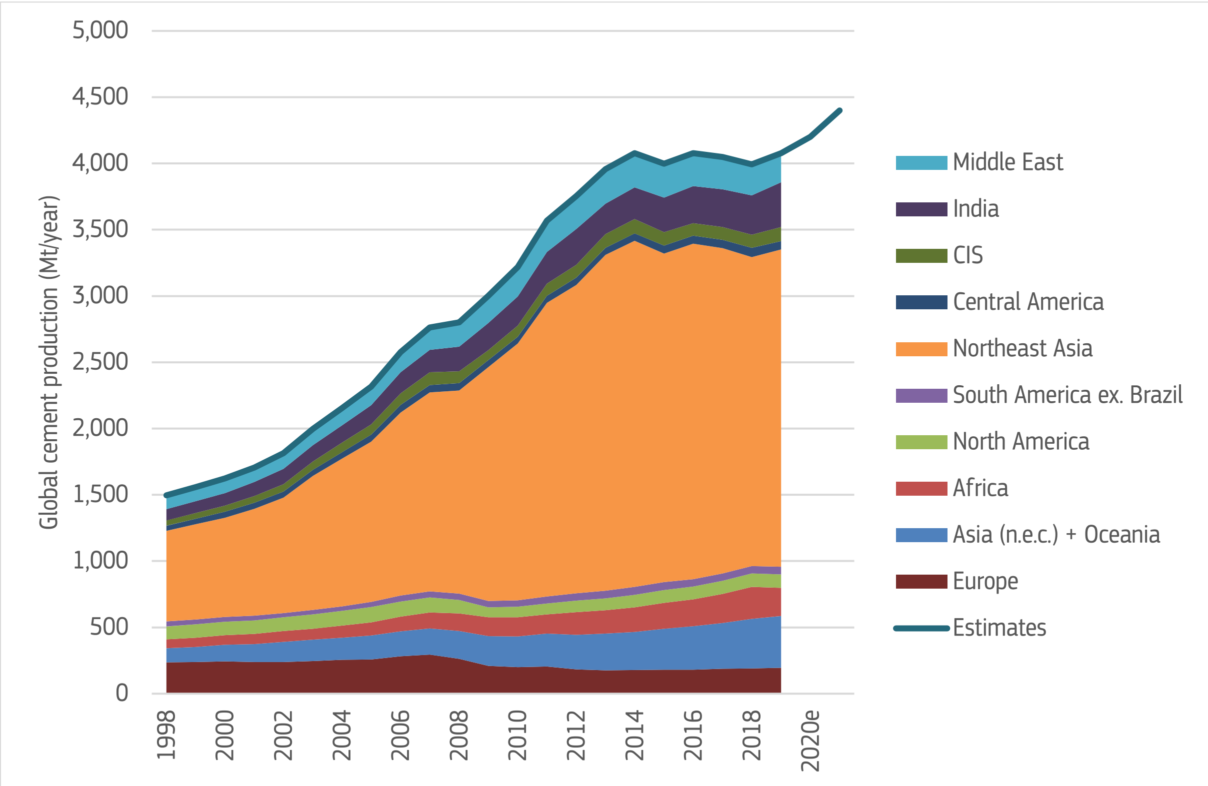
3.2.1 Cement production in the world and in the EU

Cement is one of building blocks of modern industrialised society, and one of very few materials whose production is measured in billions of tonnes. Global cement production is ever-increasing, and has more than doubled in the last 20 years. The story of cement production in recent decades has been marked by an explosion of production in China. In

1999, China was producing 36% of the world's cement; in 2019 it was responsible for 55%, or 2.3 billion tonnes, of the world's total cement production (**Figure 6**). In the same time period, the EU's share of global cement production has diminished, from 10% in 1999 to 5% in 2019. As for the COVID crisis and the tensions on Europe's eastern borders, which happened over the last two years and are thus too early for being properly accounted for, effects in terms of global cement production are estimated to be negligible, with a global production expected to resume its growth from 2019 [USGS, 2022].

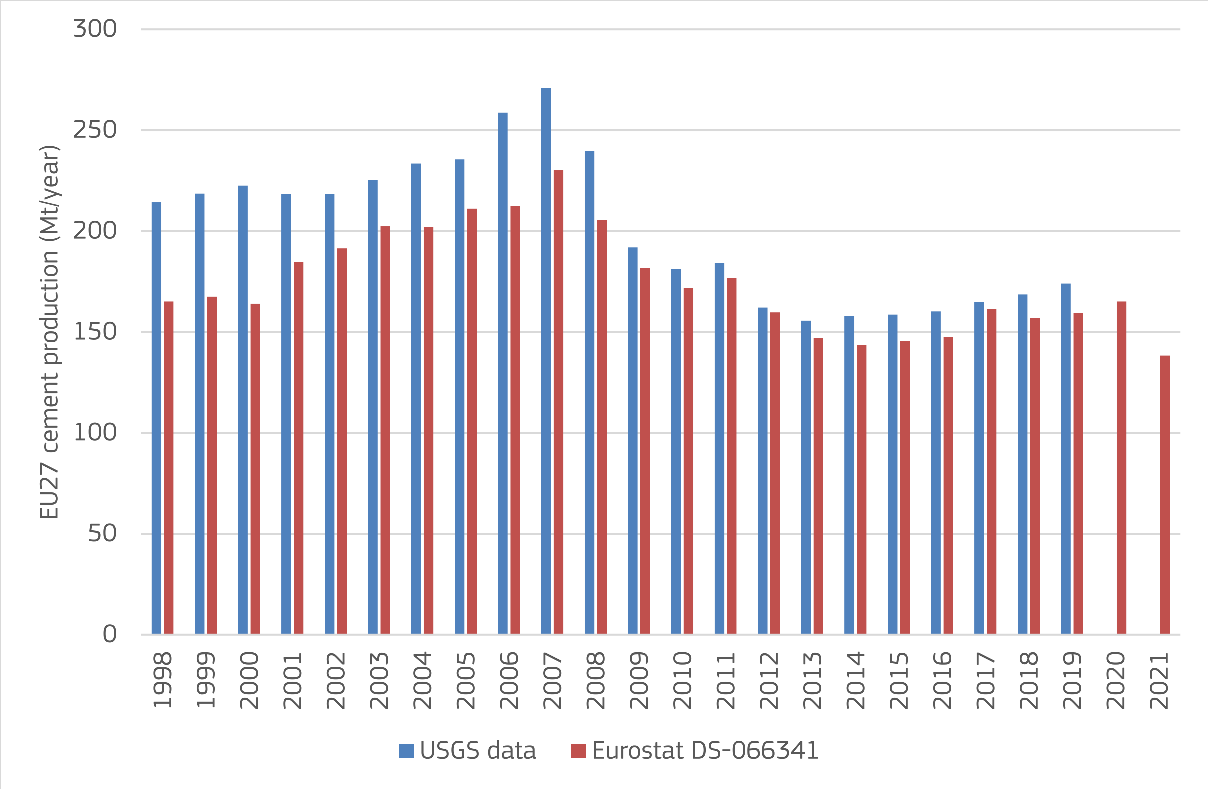
EU cement production had been strongly affected by the financial crisis, which originated in the real estate sector in 2008. The EU cement production peaked at 230 million tonnes in 2007 and declined to its lowest point over the last 20 years with a production of 144 million tonnes in 2014. Since then EU production has been steadily increasing, yet without reaching its maximum (165 million tonnes in 2020, **Figure 7**).

Figure 6 Global cement production, 2008-2020



Source: JRC based on [USGS, 2002-2019; USGS, 2022]

Figure 7 EU27 cement production, 2000-2020

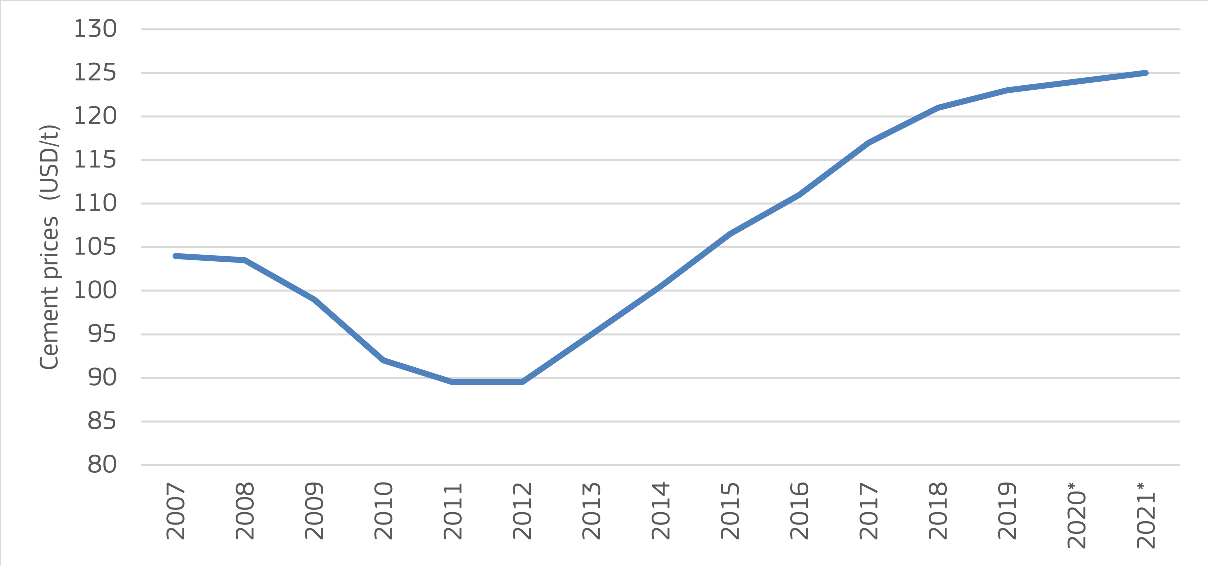


Source: JRC based on [USGS, 2002-2019; Eurostat, 2022]

In terms of prices, and considering the regional nature of this commodity, data availability is scarce. US pricing seems to follow economic macro-trends (**Figure 8**), while cement value ([1]) in the EU remains in a narrower bandwidth of 50 to 80 EUR/t since 1995 [Eurostat, 2022]. Variations on the EU market are even more contained, since cement value breached the 70 EUR/t barrier for the first time in 2007 (thus remaining in the 50 to 70 EUR/t bandwidth between 1995 and 2006), and never fell below this value again (thus remaining in the 70 to 80 EUR/t bandwidth since 2007). Fuel cost is expected to play a significant role in the future in Europe [CWGRP, 2022] and beyond, with the price of pet coke tripling since 2021 [GCD, 2022] and the price of electricity being linked to reduction in production capacity [Cemnet, 2022; Global Cement, 2022a].

([1]) As per the approach described in [European Commission, 2018], value is determined at the factory gate, thus excludes components of price such as transport to the customer.

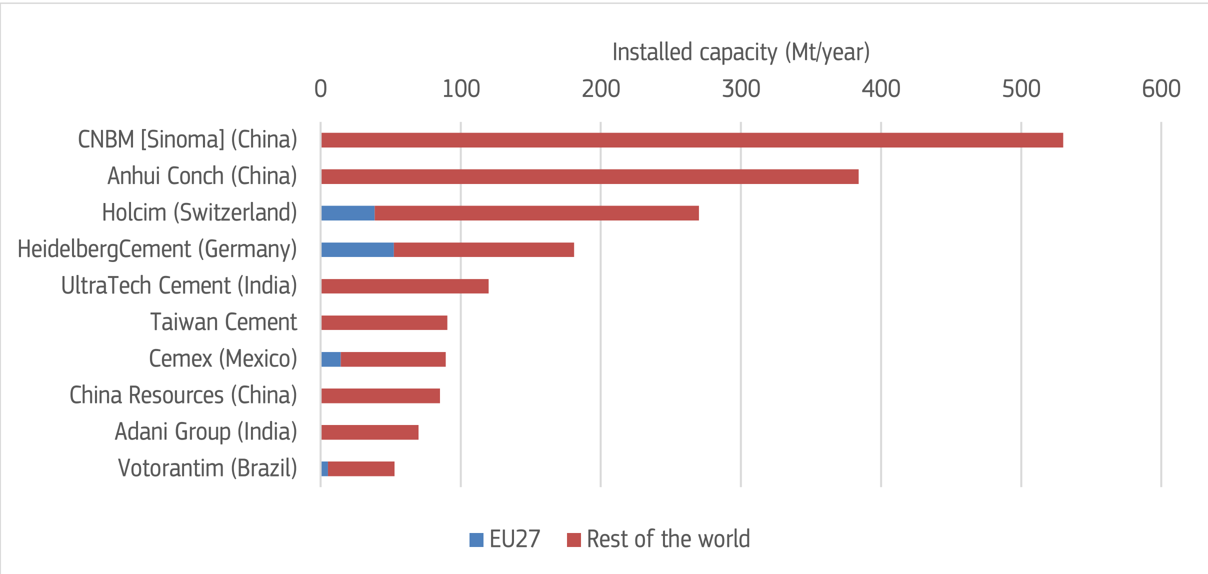
Figure 8 Price of cement in the United States, 2007-2021



Source: JRC based on Statista, 2022

Few major operations took place in the top 10 cement producers since the merger of Holcim and Lafarge in 2016 and of CNBM and Sinoma in 2018. As such the list of key cement producers worldwide remains fairly stable (**Figure 9**). Two third of the global cement are being produced by one of the top 100 cement companies [GCD, 2022]. Yet restructuring at country level are numerous [Global Cement, 2022b]. Most significantly, Holcim initiated in 2021 a divestment phase, selling assets in India, Brazil, Ghana, Malawi, Zambia and in the Indian Ocean [Global Cement Magazine, 2022].

Figure 9 Installed capacity of selected top 10 cement producers worldwide, 2021



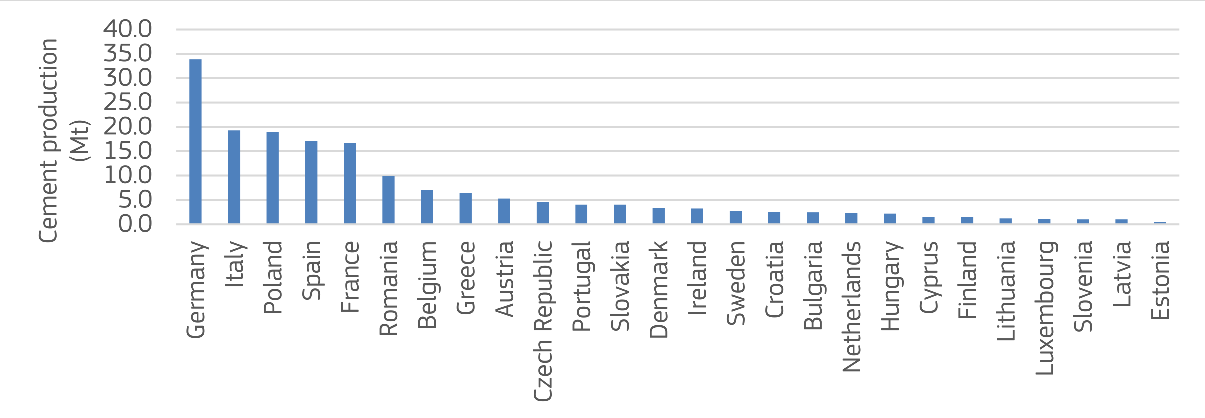
Source: Global Cement Magazine, 2022

3.2.2 Cement production in the EU

Due to high share of transportation in overall costs, cement is produced almost everywhere in the EU (**Figure 10**): Only Malta and the Netherlands do not have integrated cement plants

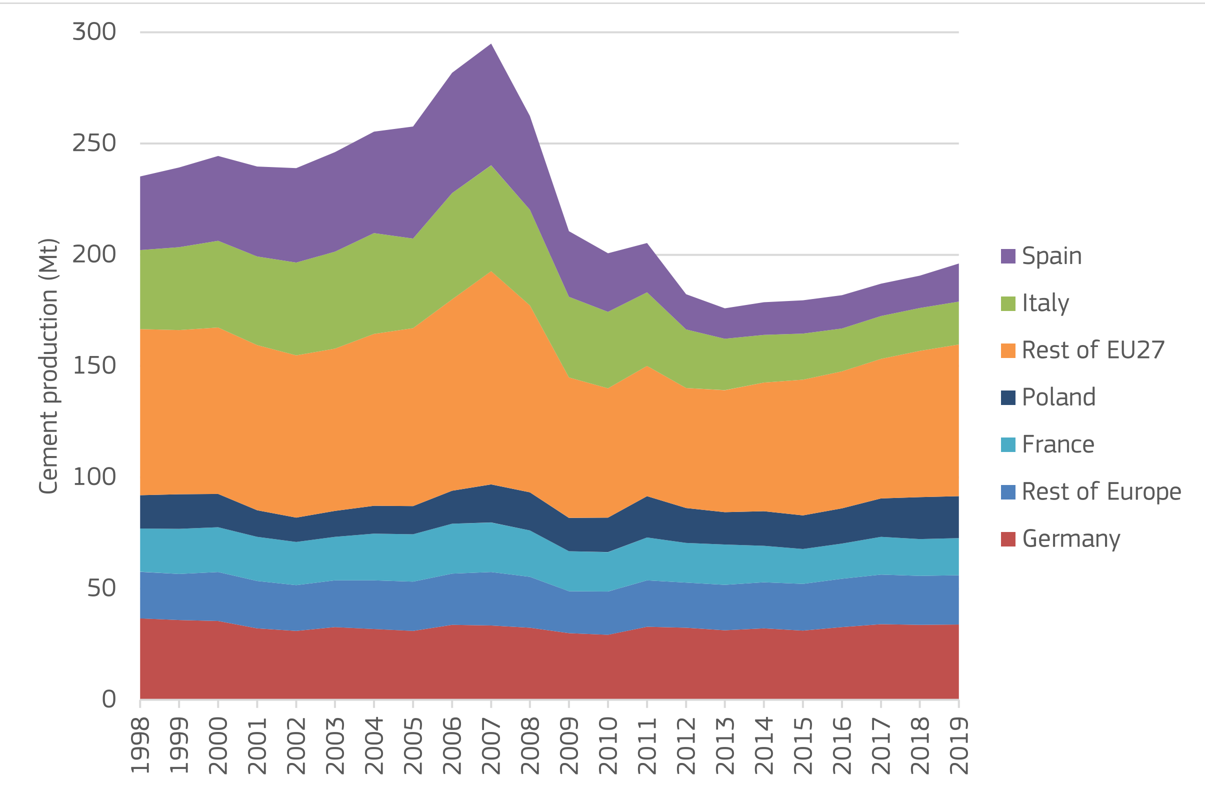
[GCD, 2022]. Germany produced 19% of all EU cement in 2019, followed by Italy and Poland (11% each), France and Spain (10% each) [USGS, 2002-2019]. **Figure 11** shows how this production evolved over the last two decades, with Spain and Italy being the most affected by the 2008 financial crisis.

Figure 10 Cement production in EU27 - 2019



Source: JRC based on [USGS, 2002-2019]

Figure 11 Cement production in Europe - 1998-2019



Source: JRC based on [USGS, 2002-2019]

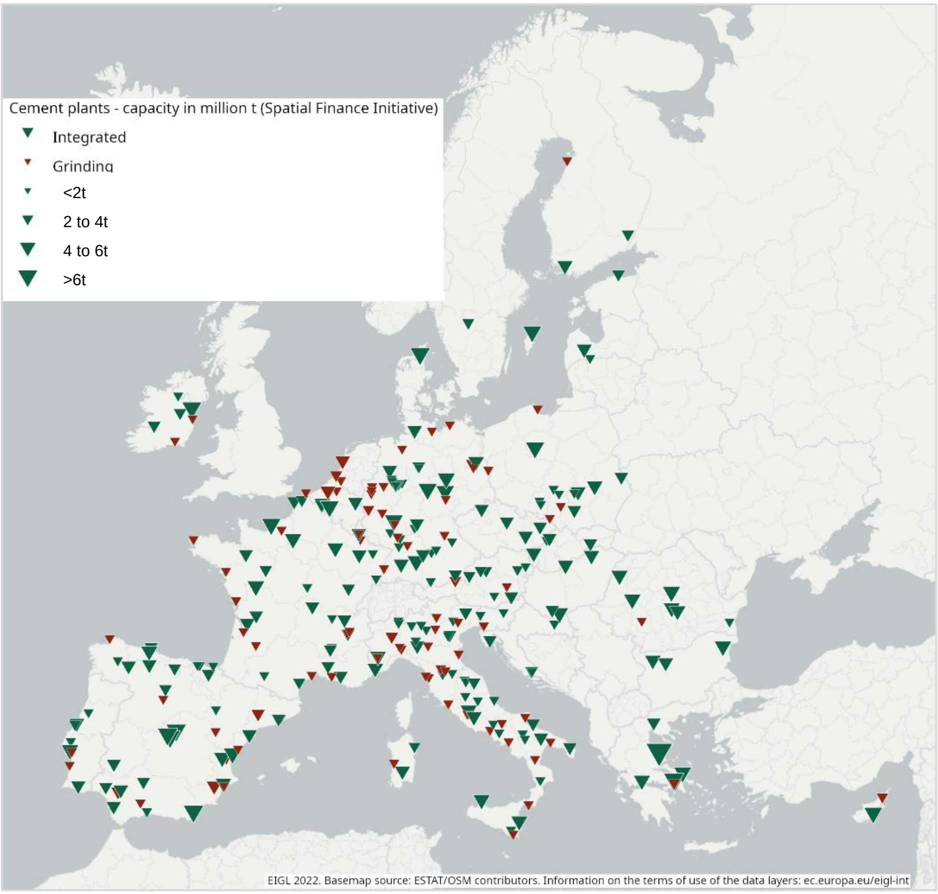
Looking at the European market, the vast majority (over 150) of the approx. 200 cement integrated plants in Europe (**Figure 12**) are (eventually partially) owned by a group which holds three or more plants. In addition to global players (displayed on **Figure 9**, including Holcim; HeidelbergMaterials (in this report still referred to as HeidelbergCement); CEMEX and Votorantim), 12 smaller groups (with three or more plants) are active in the EU.

Table 3 Cement groups and their capacity in the EU (Mt/year)

Company	**Number of plants**	**Capacity (Mt/year)**	**Company**	**Number of plants**	**Capacity (Mt/year)**
Holcim	29	39.5	Schwenk	6	7.5
Heidelbergcement	41	50.8	Titan	4	6.9
Cemex	10	14.3	Vicat	5	5.2
Votorantim	5	5.3	Cementir	2	4.4
Buzzi Unicem	16	19.3	SECIL group	3	4.0
CRH	16	16.6	Tudela Véguin	3	3.7
Valderrivas	6	9.9	Other	33	30.1
Colacem	6	7.7	**Total**	**185**	**225.2**

Source: JRC based on [GCD, 2022]

Figure 12 Cement facilities in the EU

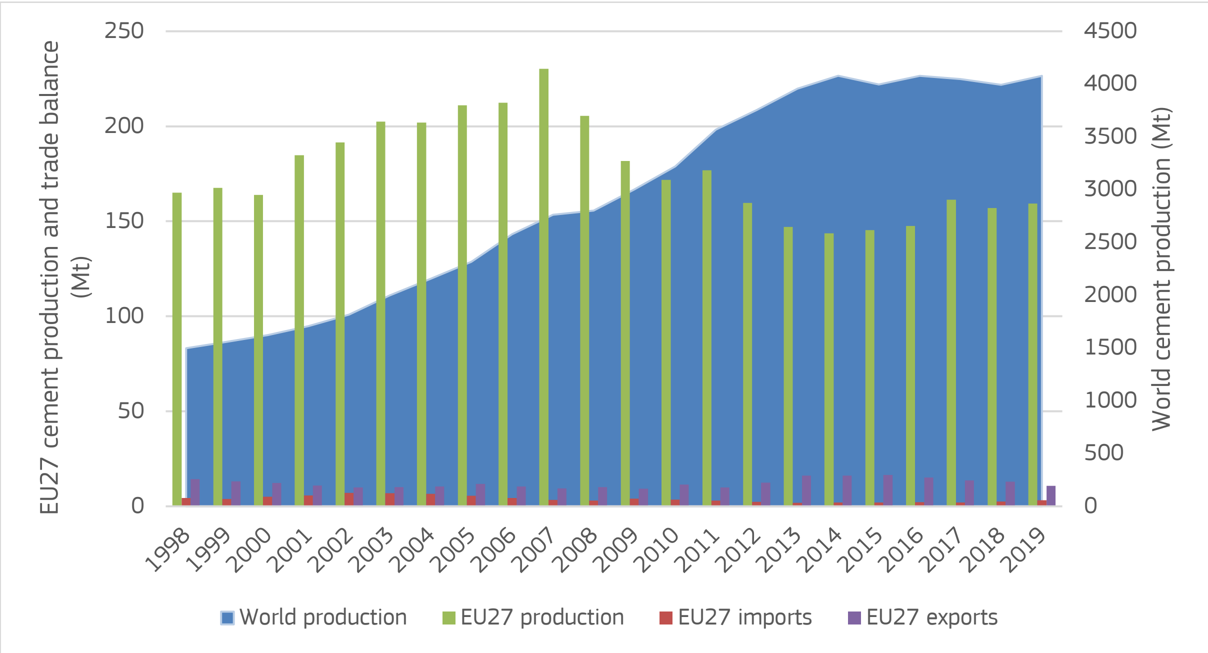


Source: JRC/EIGL based on [McCarten et al. 2021]

3.2.3 Trade between the EU and the rest of the world

With EU cement production being affected by the 2008 financial crisis and most of EU production in the hand of international groups, trade in cement at the borders of the EU did increase. However volumes traded remained marginal (max. 10% of EU production for either imports or exports) and above all positive: i.e. the EU remains a net exporter of cement-related products. There are however disparities across the cement-related products: The EU has been consistently a net exporter of cement, while it relied on imports to meet its demand in clinker before the financial crisis and again in 2021.

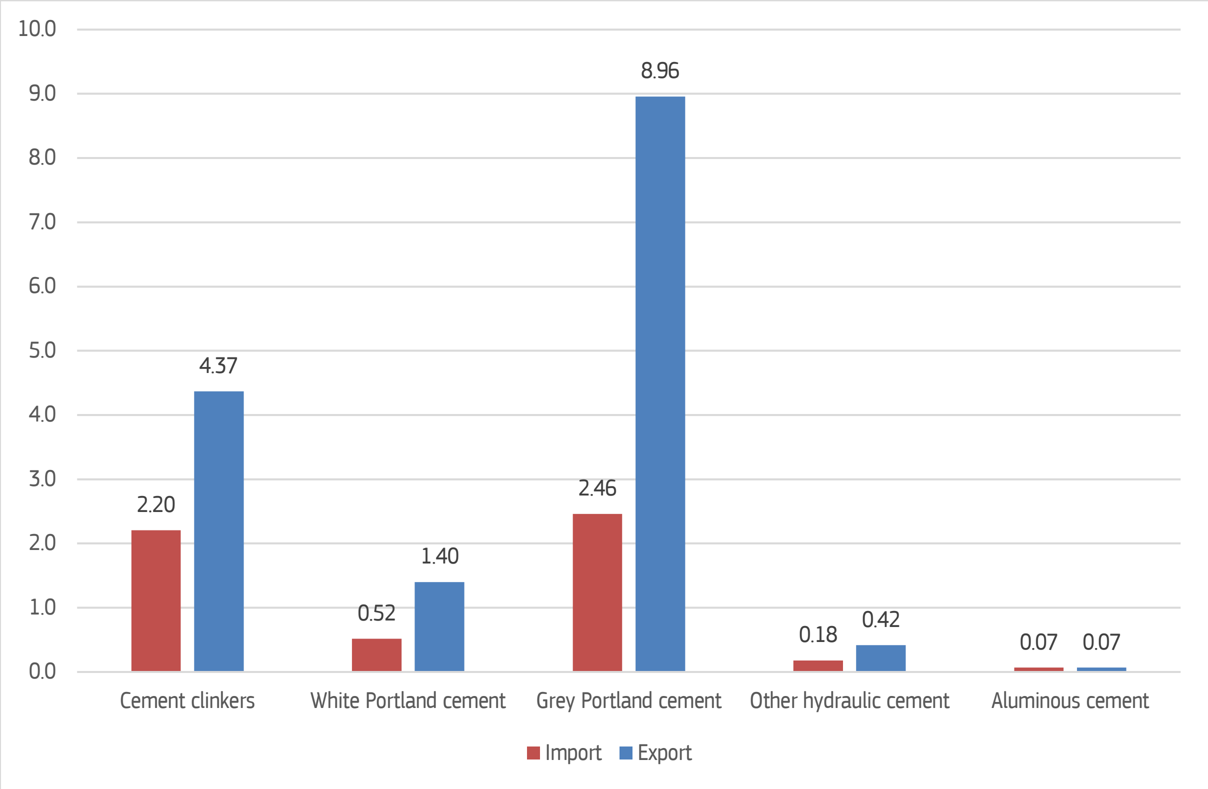
Figure 13 Global and EU27 cement production and trades between both parties, 1998-2019



Source: JRC based on [USGS, 2002-2019; Eurostat, 2022; United Nations, 2003]

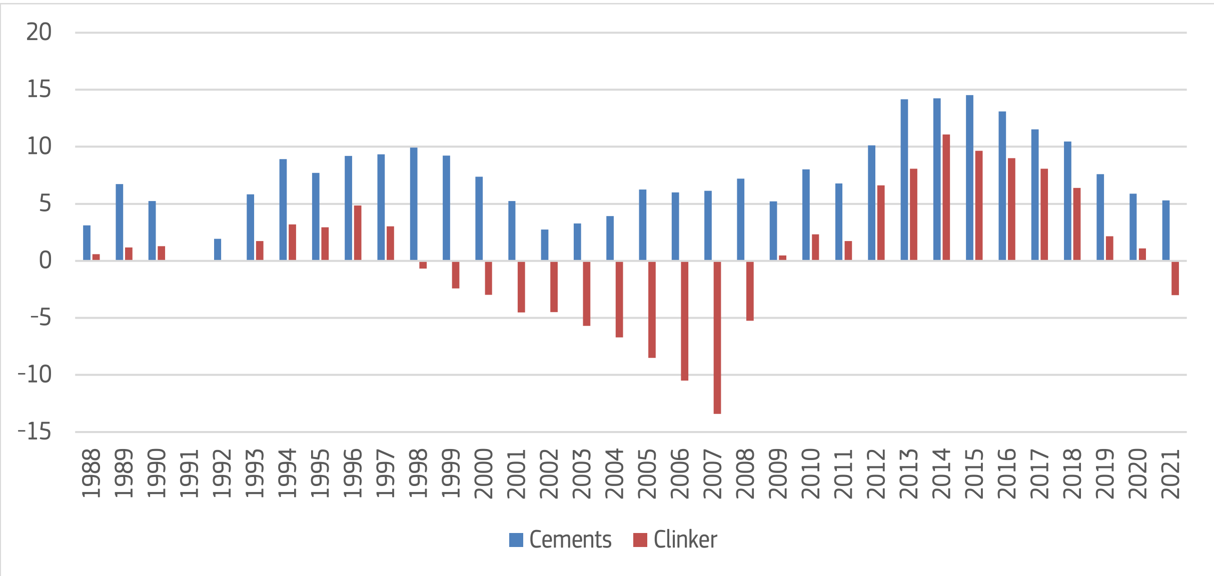
In 2019, Portland cements represented 55% of EU27 cement-related imports, followed by clinker (for 41%), non-hydraulic cement, such as supersulfated cements (for 3%) and aluminous cements (for 1% of cement-related imports).

Figure 14 EU27 imports and exports of cement-related products, 2019 (Mt)



Source: JRC based on [United Nations, 2003]

Figure 15 EU27 trade balance (exports minus imports) of cements and clinker, 1988-2021 (Mt)



Source: JRC based on [United Nations, 2003]

Trades are important from an economic perspective. However they also imply an environment impact, especially for such CO_2 intensive products.

3.2.4 CO_2 emissions of cement making

The cement industry emits approximately 7% of global CO_2. The majority of these emissions come from the calcination of limestone for the production of clinker, the most prevalent component of Portland cement (which is itself the essential binding agent in concrete). Cement and concrete emissions can be reduced by:

- deploying concretes with better performance (i.e. less concrete needed in construction);
- using concrete with alternative compositions (i.e. less cement needed in concrete, as cement content in concrete may already vary between 260 kg/m^3 and 400 kg/m^3 depending on the application [EN 206, 2021]);
- and reducing the clinker content of cement (i.e. less clinker needed in cement).

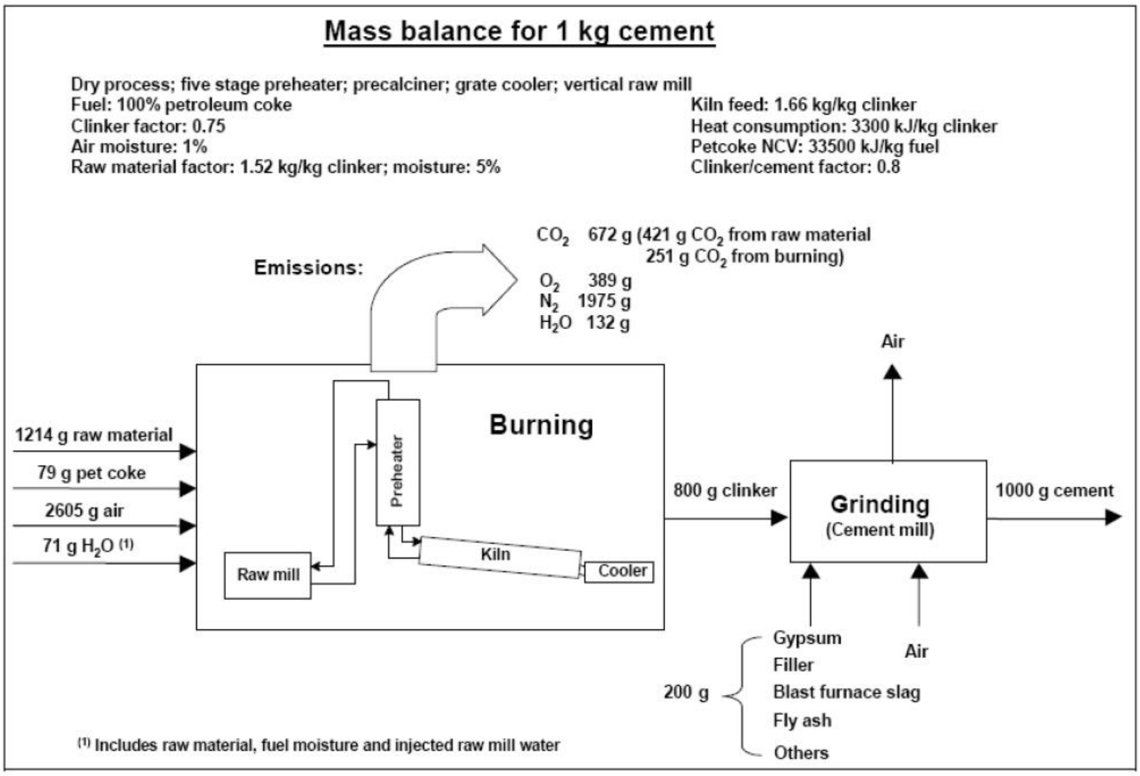
Further emissions come from the thermal processes necessary for the production of clinker, as well as electricity consumption for the production of clinker (grinding of raw materials and operation of kiln and ancillaries) and the production of cement (milling of clinker and additives).

While greenhouse gases can be accounted for in different ways (e.g. along ISO 14067, GCCA Cement CO_2 and Energy Protocol [GCCA, 2020] or the greenhouse gas protocol [GHG Protocol, 2022]), a proposal for accounting CO_2 emissions in the cement industry would be that:

- Scope 1 emissions include the CO_2 released by the calcination of calcium carbonate into calcium oxide (526 kgCO_2/kg clinker [European Commission, 2013b]) and the emissions from fuel combustion for the thermal processes for the production of clinker (which depends on the production process and type of fuel, thus theoretically ranging from 0 kgCO_2/kg clinker (for biomass-fuelled plants) to 685 kgCO_2/kg clinker (for wet process requiring 6.4 GJ/t clinker [European Commission, 2013b] fuelled by oil shale with a CO_2 intensity of 107 kgCO_2/GJ [GCCA, 2020]));
- Scope 2 emissions include the CO_2 released for the production of electricity consumed in cement making (the electricity is mainly consumed in grinding raw materials, the clinker and additives and in minor measure operating the kiln and ancillaries). In 2019, each tonne of grey and white cement required 113.5 kWh [GCCA, 2019], well within the range of 90 to 150 kWh/t cement [European Commission, 2013b]. Based on EU27 average CO_2 intensity of electricity (255 gCO2/kWh [European Environmental Agency, 2022b]), electricity implies an additional 29 kgCO_2/kg cement;
- Scope 3 emissions include the CO_2 released through the sourcing of raw materials and trade of intermediate products. This is not assessed here.

The above mentioned scope 1 / process emissions are defined for clinker, cement key component. However, the content of clinker within cement (referred to as clinker-to-cement ratio) can vary depending on the type of cement produced (see 3.3.1). This implies that CO_2 emissions of clinker are “diluted” when clinker is partially substituted with other materials of low or even zero carbon footprint for the production of cement (**Figure 16**).

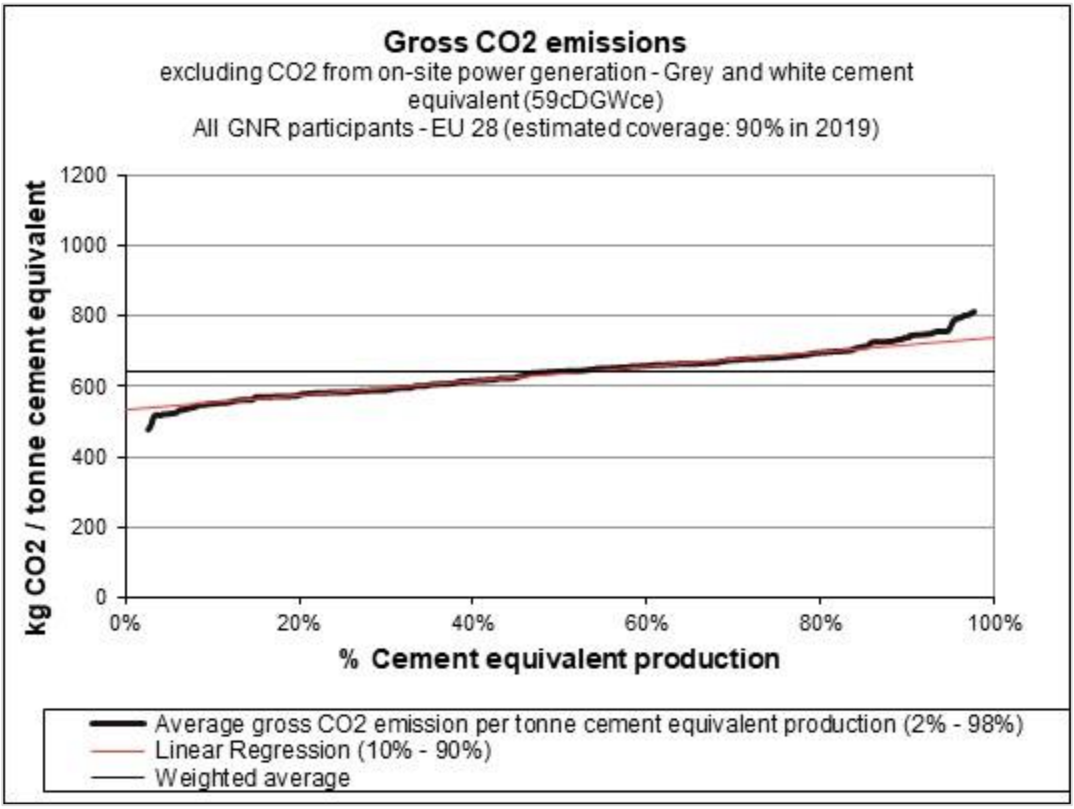
Figure 16 Mass balance for 1 kg cement



Source: [European Commission, 2013b]

Further, since the fuel mix and CO_2 intensity of electricity are dependant of the plant location, the parameters need to be accounted for at plant level for deriving accurate CO_2 emissions. All in all, grey and white cement CO_2 intensity in Europe ranges from less than 500 kgCO_2/t cement to over 800 kgCO_2/t cement (**Figure 17**). It should be noted that CO_2 emissions from the combustion of biomass is accounted for in Getting the Numbers Right initiative of the Global Cement and Concrete Association (GCCA), while biomass is deemed carbon neutral under the European Commission ETS.

Figure 17 CO_2 emissions from grey and white cement in EU28 in 2019



Source: [GCCA, 2019]

The above mentioned parameters are thus investigated more in detail in the following section.

3.2.5 CO_2 intensities in the EU and third countries

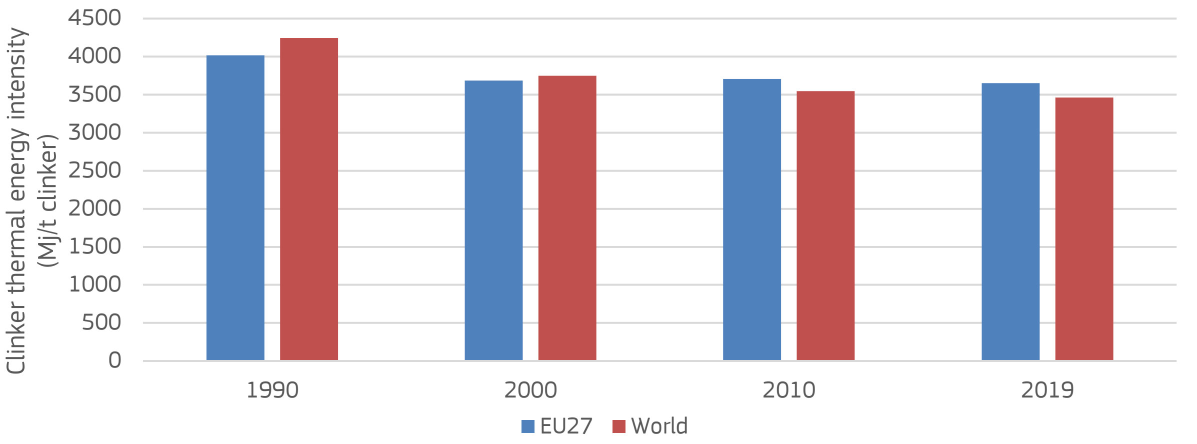
The CO_2 intensities of cement making vary across the globe. The main factors influencing the average CO_2 intensity are the technology used (either wet, semi wet, dry, semi-dry with pre-calciner or preheater), the clinker to cement ratio and the fuel mix in every country, i.e. how much clinker is needed for cement; how much and which fuels are used for the thermal processes yielding clinker.

Evolution of technology

In 2019, the most efficient process (i.e. Dry with preheater and pre-calciner) required 3.51 GJ/t clinker (on global average and for the production of grey clinker), while less efficient processes such as wet or shaft kilns required 5.51 GJ/t clinker. For white cement, irrespectively of the process used, the value reach 6.38 GJ/t cement, which implies an even higher intensity for white clinker [GCCA, 2019]. These values are consistent with technology developments [European Commission, 2013b].

Newest (and more efficient) processes are more likely to be found in countries which recently saw high economic growth and met their demand for cement through additional production capacity [ECRA & WBCSD/CSI, 2017; ISAL, 2021]. This upgrade translates in a reduction of 18% in global energy intensity of clinker between 1990 and 2019. In the case of the EU, the reduction has been marginal between 1990 and 2019 (9%) and almost nihil since 2000 (**Figure 18**). This can be correlated with the evolution of production process over the period (**Figure 19**).

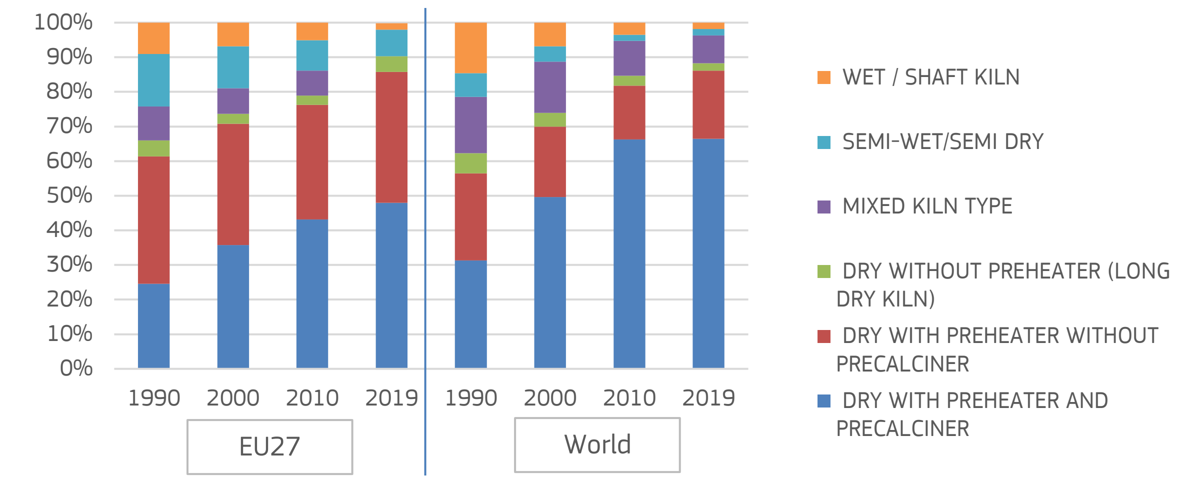
Figure 18 Clinker thermal energy intensity in EU27 and at global level (Mj/t clinker)



Notes: Data in GCCA Getting the Numbers Right initiative are reported voluntarily. This implies that data coverage is not homogeneous across world regions: For instance, the data set relies on data for 90% of the EU27 cement production and 22% for the global cement production.

Source: JRC based on [GCCA, 2019]

Figure 19 Share of technologies in the grey clinker production, in the EU27 and at global level (%)



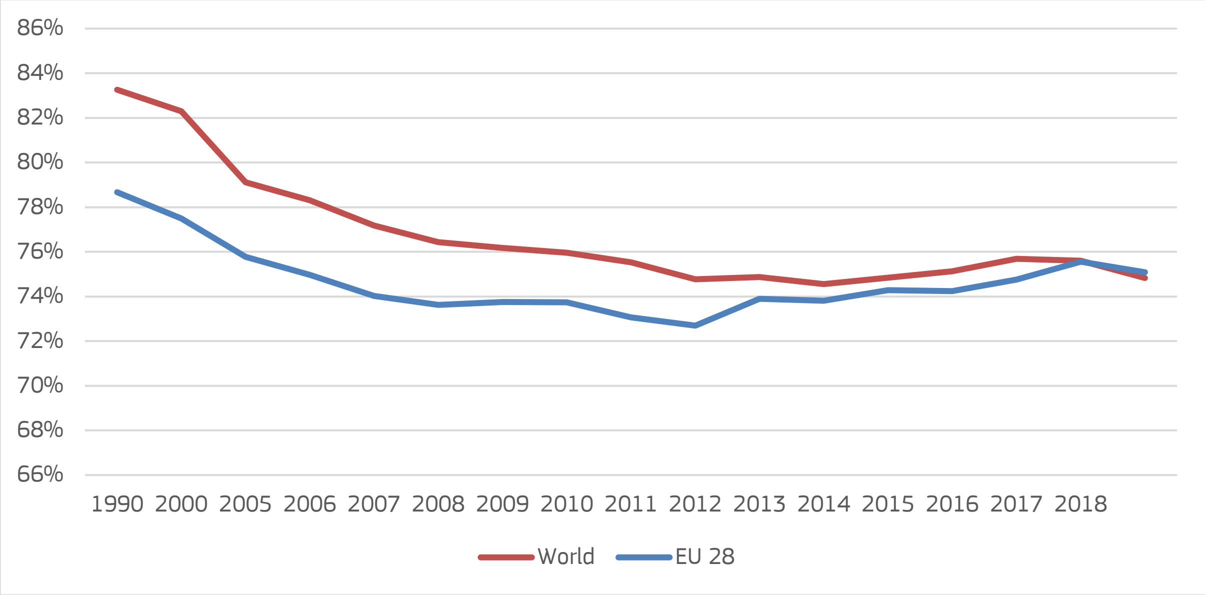
Notes: Low data coverage for specific regions in GCCA Getting the Numbers Right initiative may alter the accuracy of the results: One can for instance expect that new plants (with higher thermal efficiency) are more accurately represented than older plants (with lower themal efficiency).

Source: JRC based on [GCCA, 2019]

Clinker to cement ratio

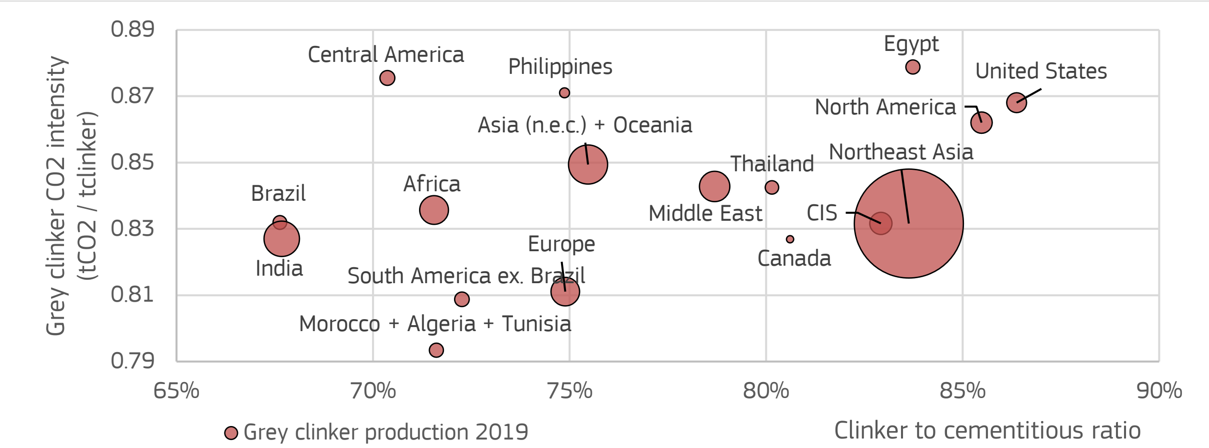
The clinker-to-cement ratio indicates how much clinker is needed per tonne of cement. While the EU clinker-to-cement ratio decreased in the first decade of the 21st century, it sees a rebound since. As noticed in China [IEA, 2021], by far the largest cement producer and thus driving global emissions, such a rebound could be linked to EU cement overcapacity, reducing the drive to substitute clinker in cement [ETH, 2018].

Figure 20 Evolution clinker to cementitious ratio between 1990 and 2019 (%)



Source: [GCCA, 2019]

Figure 21 Average CO_2 emission intensity for grey clinker, share of clinker to cementitious ratio and 2019 grey clinker production by world regions



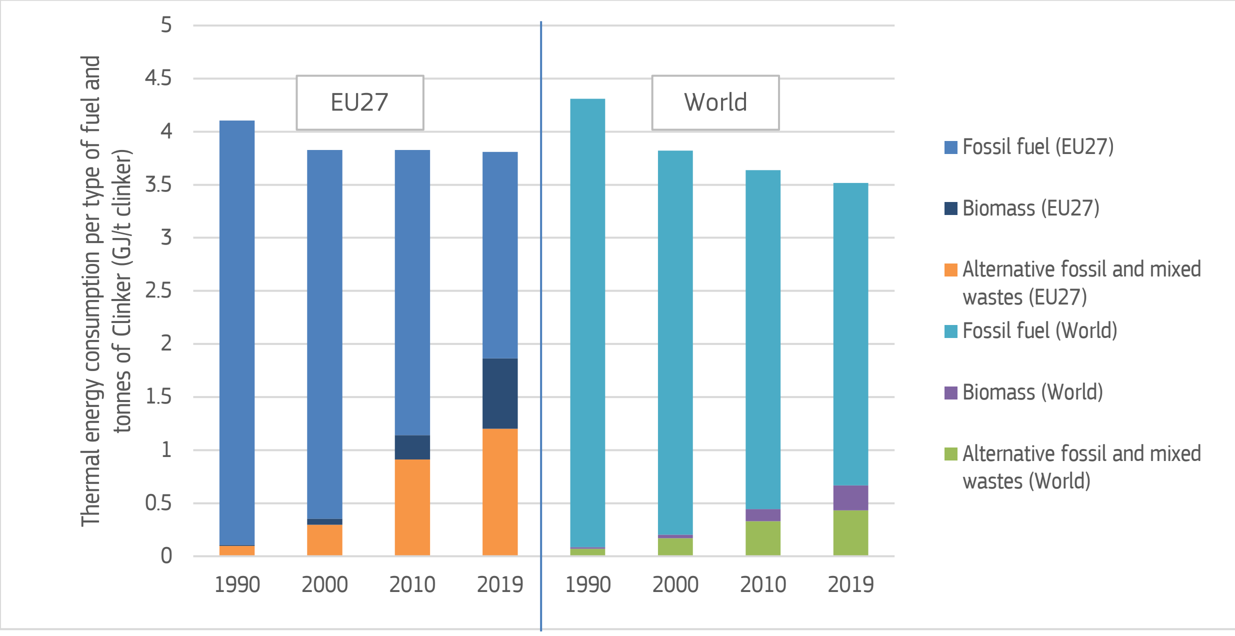
Notes: Data in GCCA Getting the Numbers Right initiatives are reported voluntarily. This implies that data coverage is not homogeneous across world regions. Further, emissions from biomass are accounted for in the clinker CO_2 intensity. This deviates from CO_2 intensity calculations performed for the EU ETS.

Source: JRC based on [GCCA, 2019]

Biomass

When looking at the fuel powering the thermal process, biomass is deemed carbon neutral under the ETS [EASAC, 2020]: A higher share of biomass is thus associated with lower CO_2 emissions being accounted for. The European shift towards alternative fuels and waste may be driven by economics (relying on cheap resources locally available). Since alternative fossil fuels and wastes have a lower CO_2 intensity than pet coke [GCCA, 2020], both types of fuel are deemed reducing emissions in cement production [Cembureau, 2013].

Figure 22 Clinker thermal energy intensity by fuel category in EU27 and at global level ([2]) (Gj/t clinker)



Source: JRC based on [GCCA, 2019].

3.3 Standardisation and circularity: levers towards CO_2 reduction

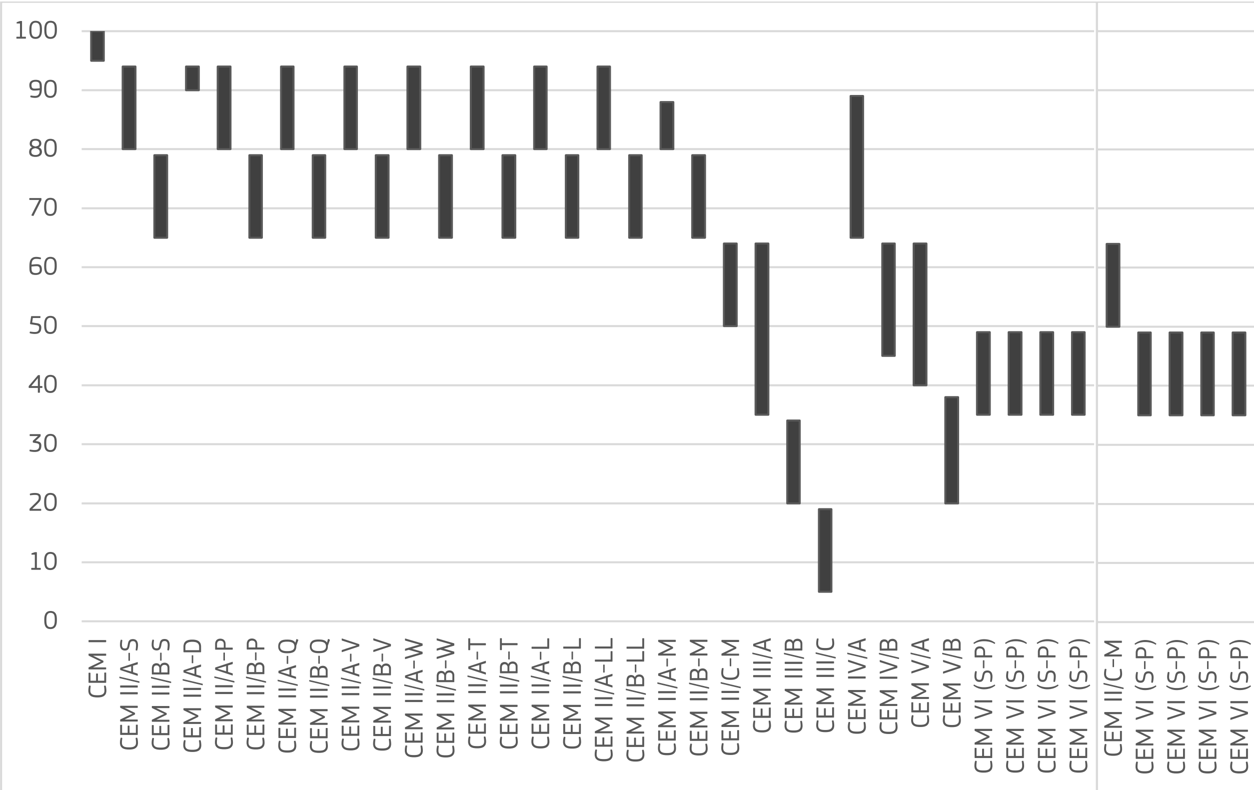
3.3.1 Standardisation for lowering clinker to cement ratio

Standardisation can help to facilitate the market uptake of low-carbon cements and concretes [ECOS, 2020; Cembureau, 2020c], thereby reducing the greenhouse gas intensity of this industry. This calls for standards aimed at: a) specifying alternative concrete and cement compositions; b) setting requirements for physical characteristics of the – then newly developed – products (be it concrete or cement); or c) harmonising products and testing methods.

European standard EN 197 addresses the composition of most common cements. EN 197 accounts for alternative cements with substitutes to clinker, such as granulated blast furnace slag, pozzolanic materials, fly ash, limestone, and silica fume. The latest addition [EN 197-5, 2021] allows further reduction of the clinker content of cement by increasing the share of these alternative materials.

([2]) the data set relies on data for 90% of the EU28 cement production and 22% of the global cement production.

Figure 23 Share of clinker (%) for cements of [EN 197-1, 2011] (left) and [EN 197-5, 2021] (right)



Source: JRC based on [EN 197-1, 2011; EN 197-5, 2021].

Regarding concrete, requirements on specification and performance are provided by European standard EN 206. This standard is not harmonised at European level, weakening the EU market for concrete. Furthermore, it does not explicitly address cements newly covered by standard EN 197-5. These cements may nonetheless be used provided that suitability is demonstrated. Standards thus need to be continuously updated to allow easier use of new clinker substitutes in cement and of admixtures as cement substitutes in concrete [NewClimate, 2020].

Alternatives to ordinary Portland cement with lower CO_2 intensities are being developed through different processes and chemistries [Gartner & Sui, 2018]. Belite-Ye'elimite-Ferrite and calcium silicate clinkers are deemed promising chemistries [ETH, 2018; Chatham House, 2018], although they do not yet comply with EU (composition) standards for cements [Gartner & Sui, 2018; Chatham House, 2018]. Yet substitutes to clinker do exist at varying phases of technological development [Chatham House, 2018; WorldCement, 2014] such as Solidia [Solidiatech, 2022], under production since 2014 [Noë, H., 2021], and Celitement [Möller, H., 2021], produced in a pilot plant between 2018 and 2021 [Celitement, 2022]. Since the composition of these cements are not reflected in current standards, there is thus room for further standards.

3.3.2 Circularity for reducing the impact of raw materials

Concrete is a CO_2 intensive material, highly consumed across the globe. Various approaches are investigated for limiting the environmental footprint of this material. The EU Waste Framework Directive calls for reuse, recycling or recovery of construction and demolition waste (CDW) [NewClimate, 2020]. This circularity would indeed enable the reduction of CO_2 emissions in the building industry. Options for circularity include the re-use of concrete components; the use of concrete waste as aggregates for fresh concrete and the re-use of cement paste into cement, concrete or binders. This latter option consists in the disaggregation of waste concrete into gravel, sand and the cement paste [SITRA, 2018]. Cement paste can then be recycled as raw material for cement production or a substitute to cement [Cembureau, 2013; ETC, 2018; ETH, 2018]. Considering ongoing technological developments, it is expected that 100% of hardened cement paste, from waste concrete offered to recycling, will be separated from aggregate and sand by 2030 [Ottelé, M., 2021]. Due to the initial hydration, this cement paste lost most of its reactivity and cannot be used as fresh cement [van Ekenstein, A., 2020]. Research is ongoing for the recycling of hydrated cement paste, indicating that de-hydration and further thermal treatments could reactivate cementitious phases at lower CO_2 intensity than fresh cement [Zhutovsky & Shishkin, 2021]. Further, there is a share of cement which remains un-hydrated within concrete and can potentially be recovered and reused [ETC, 2018]. Feeding materials (including CDW) into cement kilns is not straightforward from a chemical [European Commission, 2013b] and a standardisation [VEEP project del. 7.6, 2021] point of views. And CDW is not foreseen by current standards as an additional constituent to clinker in cement [EN 197-1, 2011; EN 197-5, 2021] or to cement in concrete [EN 206, 2021]. Yet, the use of CDW remains a topic of further research and (demonstration) testing [VEEP project, 2016; BNB project, 2018; RECEMENT project, 2018], also in industry [Holcim, 2020; HeidelbergCement, 2022].

3.4 Future demand for cement and alternatives to cement

Global cement production grew strongly up to 2013 (+164% since 1998) and remained idle since at around 4 Gt. EU cement production displays an even more turbulent history (**Figure 7**). When drivers to past demand are difficult to understand, the future demand and production for cement is likely to evolve while remaining within reasonable boundaries (such as 200 kg/capita in the UK and 600 kg/capita in Spain and Ireland in 2010) [GlobBULK, 2018]. Forecast and foresight approaches provide insights on what the future may be. The best way to reduce emissions of the cement industry is to look on the demand side, reducing primary demand for cement. Alternative materials, including waste and wood, can be used; and material intensity can be improved [NewClimate, 2020]. This includes lifetime extension of concrete structures [ISAL, 2021], component reuse [ISAL, 2021] and concrete recycling [ETC, 2018]. Some of these approaches are described below, though they are outside of the focus of this report, looking on the CO_2 intensity of cement.

3.4.1 Future demand for cement

In order to monitor progresses towards 2050 decarbonisation target, the EU industry association (Cembureau) and the European Cement Research Academy (ECRA) assume no growth – among its members - in cement production between 1990 and 2050 [Cembureau, 2018]. At global level, a wide range of cement demand or cement production in 2050 is modelled: +12-23% compared to 2014 [IEA & WBCSD-CSI, 2018] (); around 5Gt [IEA, 2020]; above 5 Gt [Climate Action Tracker, 2017]; and up to 6 Gt [SITRA, 2018]. Further it is worth noting that older forecasts and modelling exercises offered a larger spread: [IEA & WBCSD, 2009] being more conservative; while [WWF, 2008] foresaw 5 Gt by 2030, instead of 2050.

While some of the previous studies may also include data for specific regions, dedicated studies for UK [MPA Cement, 2013]; for India [WBCSD, 2013]; for California [Hasanbeigi & Springer, 2019]; Brazil [SNIC, 2019] and Europe [NewClimate, 2020] are available. [NewClimate, 2020] provides various numbers for cement production by 2050, spreading between 166 and 184 Mt depending on the study referenced.

[ISAL, 2021] also foresees global production levels well above 5 Gt by 2050. However the production values of the 2017-2021 period do not align with the forecast over the same period. This highlights the importance of assumptions for the definitions of scenarios and modelling exercises.

The above studies rely on different parameters for their analysis: From the need for construction and infrastructures, deriving from population growth and economic development, to various ways of meeting these needs (i.e. circularity and alternative materials). While cement-related technological aspects will be further developed in the rest of this report, foresight can help in the identification of such factors as well as in the framing of the ongoing developments in wider frames.

3.4.2 Possible alternative futures impacting the cement industry

Anticipation (at large) aims at taking the best decisions now for a better future. Considering the expected lifetime of cement facilities, coupled to the capital intensive nature of this industry, future developments are of key importance. Anticipation can be done based on hard facts and forecasts (see above); Anticipation can also rely on softer facts (foresights, including horizon scanning).

Foresight is the discipline of exploring, anticipating and shaping the future to help building and using collective intelligence to anticipate developments. Foresight helps better develop possible transition pathways, prepares to withstand shocks and shapes the future. Foresight is not about predicting the future; it explores different possible futures, alongside the opportunities and challenges they might present [European Commission, 2022e].

Among approaches to foresight, horizon scanning is an activity of systematic and systemic review of recent developments to try and spot emerging issues that would require a change in behaviour, strategy, policy. To this end, JRC relies on Futures Platform ([3]), a Finnish company offering commercial support in strategic foresight and a catalogue of phenomena ([4]). Different types of phenomena, such as 'summary' (trends of broader nature), 'strengthening' or 'weakening' trends as well as (emerging) 'weak signal' and (hard to predict) 'wild card', are compiled by a team of futurists [JRC, 2022]. "Carbon-Neutral Cement" [Futures Platform, 2022a] is such a strengthening trend, detailing current progresses towards the decarbonisation of cement by 2050. In a first instance, this trend is flagged as related to other phenomena referring to the demand for building materials and how to mitigate environmental impact:

— "Doubling the Number of Buildings" [Futures Platform, 2022b] looks into the long term demand for construction, urbanisation and housing;

— "Concrete Out of Waste" [Futures Platform, 2022c] is highlighting the potential for circularity in concrete;

— "Self-Healing Bio-Concrete" [Futures Platform, 2022e], in which bacteria repairs cracks in (bio-)concrete, thereby extending lifetime of buildings (reducing demand for concrete and cement);

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(3) http://info.futuresplatform.com/hub/about-futures-platform
(4) http://info.futuresplatform.com/hub/how-content-is-produced

— Cement sustainability is only part of the equation: Concrete also requires also gravel and sand. "Sand Suitable for Building" [Futures Platform, 2022d] recalls the environmental burden of this material;
— Finally, on a longer time horizon, "Self-Maintaining Buildings" [Futures Platform, 2022f] foresees radically different approaches to construction, possibly environmentally-friendlier.

These phenomena do also refer to further phenomena. They then open-up to wider trends (linked to infrastructures, cities, urbanisation and circular economy) or narrower trends (such as synthetic biology or smart homes). While the impact of such phenomena is uncertain and thus even harder to quantify, it makes sense to keep an eye on broader developments, possibly exogenous to the cement industry, that may impact its future and drive towards sustainability.

While increasing circularity through the re-use of concrete components or recycled cement and reducing cement demand are important levers for the decarbonisation of EU cement industry, virgin cement will continue to be needed in the future. This requires the deployment of new technologies to further reduce or address CO_2 emissions.

4 Decarbonisation options: technologies and costs

The cement sector is currently exploring different strategies to reduce CO_2 emissions. Ongoing process modifications (as explored in section 4.1) and a switch from fossil fuels to low-CO_2 energy sources (Section 4.2) are already enabling CO_2 mitigation. Combined with CCUS technologies, deeper emissions cuts can potentially be achieved.

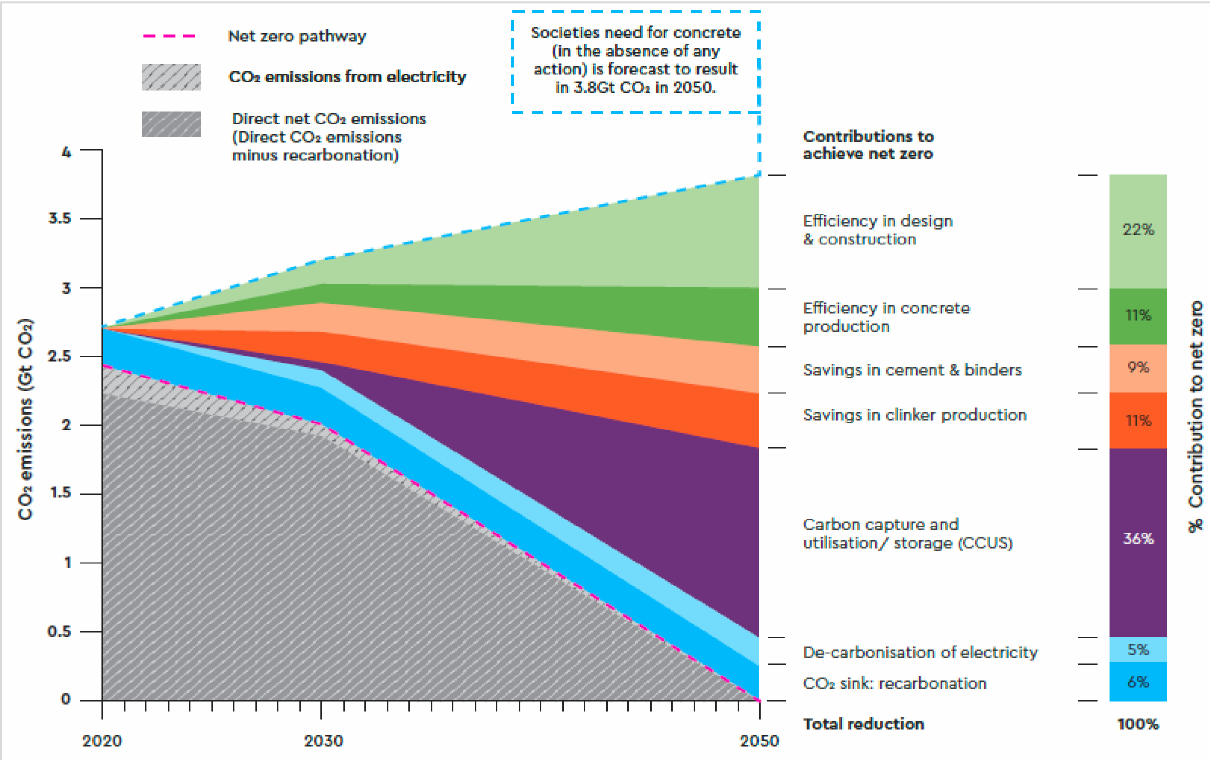
- Developing new cement formulations with lower quantities of clinker and/or other materials avoiding the calcination of carbonates (Section 4.3).
- Capturing and using the emitted CO_2 (CCU) from the cement production in the production of basic chemicals and synthetic fuels as well as through the carbonation of cement, either during curing or at end-of-life (Section 4.4).
- Considering the climate emergency, and the difficulty to truly decarbonise the economy, carbon negative cements may also provide a valuable contribution (Section 4.3.4);
- (Linked to concrete and cement demand, to be mitigated by substitution of concrete or alternative concrete structures, though this is outside the scope of this report).

Effective decarbonisation options address the sources of emissions from largest to smallest. As per chapter 3, the largest source of emissions are:

- Process emissions from the calcination of calcium carbonate, to be addressed with CCUS or mitigated with alternative cement compositions, including circularity;
- Process emissions from the combustion of fuel for remaining thermal processes, to be addressed by kiln electrification or mitigated by fuel efficiency;
- Indirect emissions, from electricity consumption, will be addressed with a decarbonised electricity system. In the meantime efficiency is a way forward;

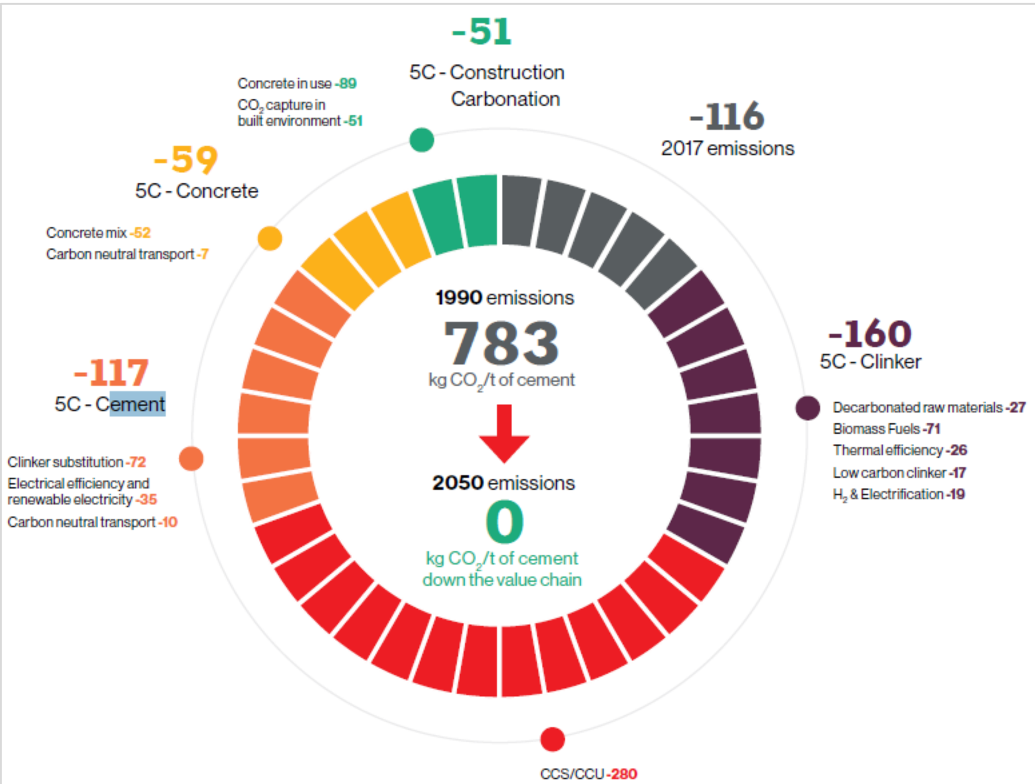
Along decarbonisation levers for the concrete sector (**Figure 24** at global level and **Figure 25** among Cembureau members), the following sections will focus on the main decarbonisation options and feasible technologies that are being pursued by the cement industry: Efficiency improvements; use of alternative fuels; use of alternative raw materials; CCUS and carbon negative cements. It is worth nothing that some of the decarbonisation options, presented in this chapter, are covered by UNFCCC Clean Development Mechanism (CDMs) [UNFCCC, 2021]. Generic one [UNFCCC, 2021a] refers to "Emission reduction from partial switching of raw materials and increasing the share of additives in the production of blended cement". Options for alternative concrete structures or compositions are not considered here, though relevant European funded projects may be listed in Annex 1. Evolution of European funding on cement decarbonisation options (**Figure 26**) indicates a steady funding on efficiency improvements, while funding on alternative fuels; alternative materials to clinker in cement and – even more – CCUS see steady increases: In total, funding on such cement decarbonisation projects increased from EUR 19.2 million in 2012 to EUR 75.6 million in 2022.

Figure 24 Quantification of decarbonisation levers for the global concrete sector, 2050



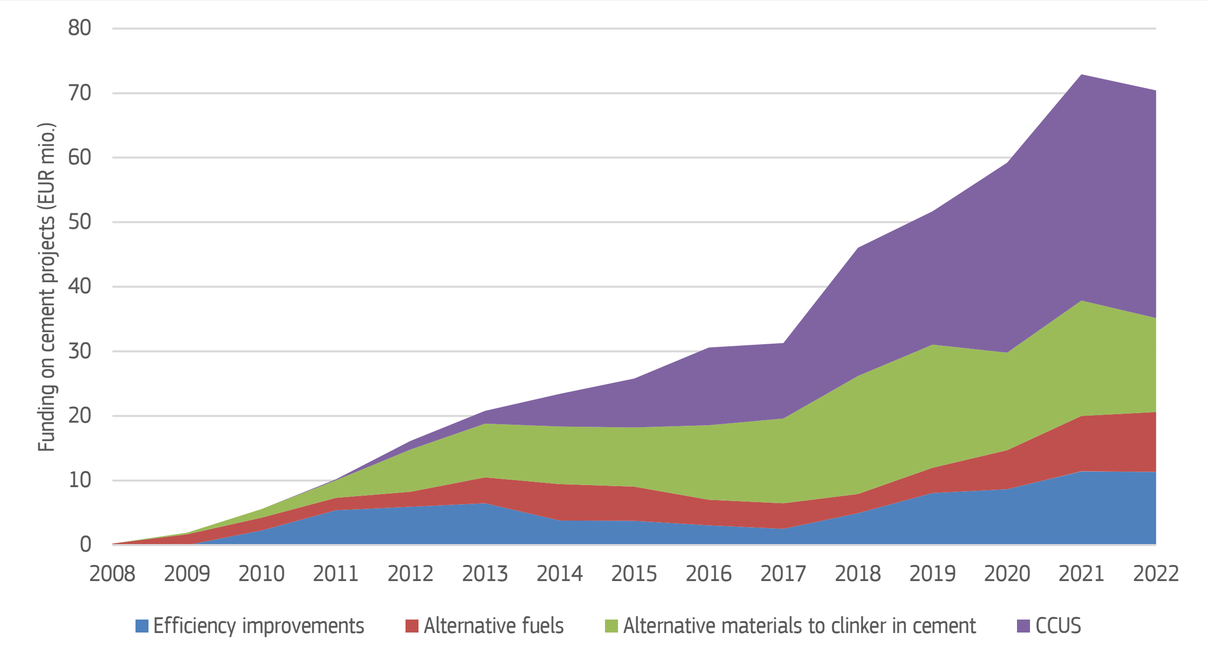
Source: [GCCA, 2021].

Figure 25 CO2 reductions along the EU cement value chain between 1990 and 2050



Source: [Cembureau, 2020c].

Figure 26 Funding on decarbonisation projects in Europe since FP7 programme



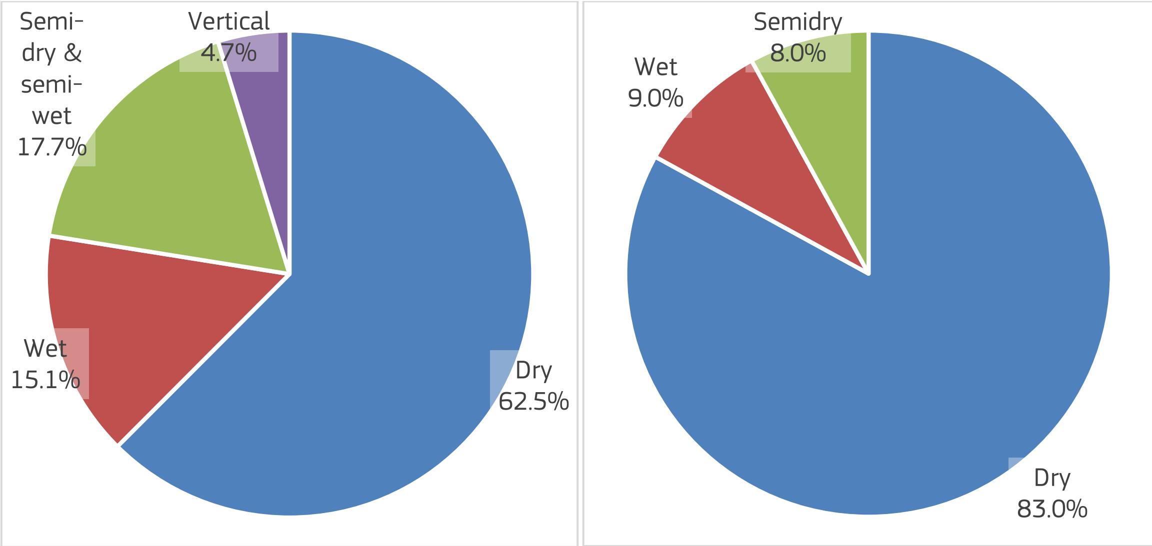
Source: JRC, based on EU-funded projects listed in annex 1

4.1 Efficiency improvements

The theoretical minimum thermal energy demand for the production of cement clinker lays between 1.59 and 1.84 GJ/t clinker [ECRA, 2016], while the EU27 and global average are at 3.81 and 3.52 GJ/t clinker for 2019 respectively (**Figure 22**). There is thus room for saving on fuel consumption and emissions. While global average could be improved to 3.15-3.215 GJ/t clinker by 2050 [ECRA & WBCSD/CSI, 2017], the best case scenario in 2019 ([5]) already requires only 2.7 GJ/t clinker [GCCA, 2019]: A 23% decrease in energy consumption. Efficiency improvements of 10-11% globally by 2050 are being reported, though with regional disparities [IEA & WBCSD/CSI, 2018]. Since thermal processes takes place in a kiln, which is a large combustion facility, increases of plant efficiency will ultimately be limited – among others - because of thermal losses; CO_2 capture and storage measures (or co-generation options); plants not using their full capacity [Lecomte et al., 2017]; as well as ongoing efforts to use best available techniques (**Figure 27**).

([5]) Production of grey clinker for the most efficient plant in India. This plant is identified with indicator 25aDG "Thermal energy consumption – excluding drying of fuels – Grey clinker" in GNR data [GCCA, 2019]

Figure 27. Share of kiln technologies for EU integrated plants, 2002 (left) 2022 (right)



Source: JRC based on [WCD, 2002; GCD, 2022].

Full capacity refers to an utilisation rate of 100% and indicates that producers' actual output matches the potential output based on fully utilised production capacity. Overcapacity refers to a market situation which does not allow for all potential product to be sold. In this situation, production is reduced by operating the facility at a lower utilisation rate. High utilisation rates are linked to improved profitability and sustainability [Global Cement, 2021]. The utilisation rate of existing production capacities influences economic performance [European Commission, 2018], with a healthy profitability enabled by a kiln utilisation rate of 75% or more [IFC, 2014]. In addition, maximum energy performance is reached at maximum design continuous loads [IEA & WBCSD-CSI, 2018] while operating at half capacity is deemed energy inefficient [Climate Strategies, 2014]. If the industry was operating at 70% utilisation rate between 2015 and 2020, the pandemic and economic slowdown are expected to worsen this overcapacity [IFC, 2020]. Yet such overcapacity is an opportunity to close the most inefficient plants [Chatham House, 2018; IEA, 2021b].

In order to improve thermal efficiency, the following measures are being investigated and/or implemented: Modernisation of process and kiln [ISAL, 2021; IEA & WBCSD-CSI, 2018; Mistra Carbon Exit, 2020]; Waste heat recovery [IFC, 2014; Global Efficiency Intelligence, 2021; IEA & WBCSD-CSI, 2018]. Lessons can also be drawn from the lime sector, which pursues – besides the above approaches - efficient insulation lining to minimise shell heat losses; improved process and input control and maintenance [ECOFYS, 2014].

The best available technology for clinker production is a dry process kiln with multistage preheating and pre-calcination. In such installation, waste heat preheats and pre-calcines the raw material feed before entering the kiln, providing up to 10% reduction in energy consumption (**Table 2**). The ongoing evolution towards thermal efficient processes (dry kiln with pre-heater and pre-calciner) (see section 3.2.4) implies using waste or excess heat [IEA & WBCSD-CSI, 2018] and the retrofitting of several plants in Europe [ATEC, 2019]. Such set-up therefore hampers the business cases for further waste heat use or other processes relying on waste heat [ECRA & WBCSD/CSI, 2017]. Waste heat can be used for “integrated use" (i.e. the drying of fuel required for the cement plant [ECRA & WBCSD/CSI, 2017]) or for external use [ECRA, 2016], including heating and power generation.

Waste heat from cement plants is used for heating purposes in various locations across the EU: Kirchdorfer Plant in Kirchdorf (AT); Cementir plant in Aalborg (DK); CRH plants in Lappeenranta and in Parainen (FI); HeidelbergCement plant in Burglengenfeld (DE) and Schwenk plant in Karlstadt (DE) [ECRA, 2016].

Waste Heat Recovery (WHR) uses a portion of the medium temperature (200-400°C) waste heat of kiln flue gases to generate electricity. Although it does not reduce the amount of electricity used at a cement plant, it uses the excess heat that otherwise would be wasted in order to generate electricity for on-site use or export to the grid [Global Efficiency Intelligence, 2021]. Options include heat pumps; steam cycle; Organic Rankine Cycle (ORC); Kalina cycle or supercritical CO_2 systems [TASIO project, 2014; Heatleap project, 2014; IFC, 2014; ECRA & WBCSD/CSI, 2017; CO2OLHEAT, 2021; AC²OCem, 2021]. Other external uses of waste heat include CCUS [ECRA & WBCSD/CSI, 2017], supplying heat to other industries and district heating [ECOFYS, 2014]. Under state's policy and regulation, China's became and remains the leader in WHR technologies [IFC, 2014], which remains marginal in Europe (**Table 4**). In addition to the ongoing or recent projects referred to in **Table 4**, WHR has been studied though not rolled-out in many facilities: Holcim's plant in Retznei (AT) [ECRA, 2016]; Cimpor's plants in Alhandra and Souselas (PT) [Cimpor, 2010; Cimpor, 2011; Cimpor, 2021a; Cimpor, 2021b]; Baumit GmbH plant in Wopfing (AT) [ATEC, 2019].

Regarding economics, WHR in the cement industry requires high capital investment costs, but has a low operational cost [EBRD, 2016]. In terms of energy efficiency, steam cycle offers a decrease in the range of 8 to 22 kWh/t clinker, while the range is smaller (between 10 to 20 kWh/t clinker) in the case of ORC and Kalina cycle. In economic terms, installations for all three types of technology cost between EUR 15 to 25 million (expected to remain constant between 2015 and 2050). All three technologies are expected to reduce cement price by 0.5 to 1.4 EUR/t in 2015, increasing to 0.7 to 1.9 EUR/t in 2050. [ECRA & WBCSD/CSI, 2017]. Costs depend on various factors, such as type of technology, size and location of installation. This introduces a wide range, from USD 7 000/kW of electricity for 2 MW systems (ORC) to USD 2 000/kW of electricity for 25 MW systems (steam) [IFC, 2018]. In the case of ORC, though not focusing solely on the cement industry, costs are estimated at around USD 1 500/kW [Tartière & Astolfi, 2017], with Levelised Costs Of Electricity comprised between EUR 21 MWh and EUR 45 MWh [Santarossa, S., 2022].

Besides thermal efficiency and making efficient use of the production facility, improving on **electric efficiency** is another avenue for CO_2 emission savings. Electricity is indeed required for the grinding of raw materials, of cement and of additives as well as for the operation of the kiln and its ancillaries. Electricity accounts for 13% of the global final energy consumption of cement making [IEA & WBCSD-CSI, 2018]. Grinding operations (or comminution) consumes up to 70% of the electric energy demand for clinker and cement production [ECRA & WBCSD/CSI, 2017]. Even though the wet process tends to disappear, several grinding technologies (and approaches) for handling dry materials are available [European Commission, 2013b]. These include grinding aids [ECRA & WBCSD/CSI, 2017] or the separate grinding of materials for high-blend cement [BZE, 2017]. However, electricity consumption of certain decarbonisation options, such as for CCUS or kiln electrification, also have to be accounted for. Electrification may drive the electricity intensity up instead of down while reducing the direct energy intensity [Climate Action Tracker, 2017].

Table 4 Selected waste heat recovery projects in the EU cement industry (as of July 2022)

Location	**Customer**	**Status**	**Supplier; technology**	**Size**
Czech Republic, Hranice	Buzzi Unicem	Project	n.a.	n.a.
Czech Republic, Prachovice	CEMEX	Under demonstration testing	Supercritical CO_2	2 MWe
Germany, Erwitte	Portlandzementwerk Wittekind Hugo Miebach Söhne KG	Awarded	Orcan Energy; ORC	8 MWe
Germany, Lengfurt	HeidelbergCement	In operation since 1999	Ormat; ORC	2 MWe
Germany, Rohrdorf	Rohrdorfer	Covers about 27% of plant power demand	Conventional steam cycle Küttner ECOFLOW Heat transfer	
Germany, Rudersdorf	CEMEX		Orcan Energy; ORC	8.15 MWe
Italy, Pederobba	Industria Cementi Giovanni Rossi		Exergy; ORC	3.6 MWe
Italy, Piacenza	Industria Cementi Giovanni Rossi	Under construction	Turboden; ORC	2 MWe
Italy, Sesto Campano	Colacem	Project	n.a.	2-3 MWe
Portugal, Outão, Setúbal	Secil-Group S.A.	Under construction	Turboden; ORC	7.2 MWe
Romania, Aleșd	Holcim	In operation since 2012	Turboden; ORC	4 MWe
Romania, Fieni	HeidelbergCement	In operation since 2015	Turboden; ORC	3.8 MWe
Slovakia, Rohožník	CRH	In operation since 2014	Turboden; ORC	5 MWe
Sweden, Skövde	HeidelbergCement		WHR boiler in the kiln off-gas down duct	n.a.
Sweden, Slite	HeidelbergCement		Conventional steam cycle	6 MWe

Source: JRC based on [ECRA, 2016; IFC, 2014; European Commission, 2013b] and company announcements [ATEC, 2019; Casale M., 2021; CEMEX, 2022; Colacem, 2020; CO2OLHEAT, 2021; Exergy, 2020; Grimekis et al., 2019; Irish Cement, 2017; Küttner, 2022; Orcan Energy, 2021a; Orcan Energy, 2021b; Ormat, 2022; SECIL, 2020; Turboden, 2022]

4.2 Use of alternative fuels

Cement is an energy intensive industry, which emits approx. 40% of its emissions through fuel consumption. These are scope 1 emissions (through thermal processes i.e. the combustion of fuel for high temperature) and scope 2 emissions (through the production of electricity consumed in cement making). While the decarbonisation of the power system is ongoing, there are avenues for addressing emissions from thermal processes [Sandalow et al., 2019]. As per **Figure 22**, the industry is diversifying its fuel mix for thermal processes: the use of waste and biomass is already gaining ground. Solar heating, hydrogen and electrification are other avenues being investigated.

4.2.1 Alternative fuels and waste

The above list indicates the difficulty to disintricate biomass and waste: diapers is classified as biomass while impregnated saw dust is classified as a waste. Irrespectively, cement kilns can burn up to 100% of waste or biomass fuels. Some plants are already operating (Allmendingen (DE) and Retznei (AT) [Cembureau, 2020c]), or being upgraded to operate under such operating conditions (Mannersdorf (AT) [ATEC, 2022]; Otterbein, (DE) [ZKW Otterbein, 2022]) while other plants are investigating the possibility to operate (Montalieu-Vercieu, [Vicat, 2021b]; Mergelstetten [Catch4climate, 2021]) without consuming fossil fuels. Trials, including using hydrogen in the fossil-free mix, were successfully conducted ([6]). This evolution is connected with the availability and cost of such fuels: cost of biomass can vary from more than USD 20/GJ (for oil crops) to USD 1-2/GJ (for agricultural residues), while the combustion of municipal waste can even be a source of revenues [ETC, 2018]. The use of municipal waste implies however to address the issue (and cost) of chlorine, which is already the case at several European plants [ATEC, 2019; FLSmidth, 2021].

4.2.2 Biomass

For biomass, the focus is on waste streams rather than proper biofuels for economic and environmental reasons [ECRA & WBCSD/CSI, 2017]. Sustainable biomass is expected to be in the range of 539 to 915 million dry tonnes in 2050. While this amount of energy could power 20 times the EU cement industry (consuming approx. 5*10^17 J in 2019 [GCCA, 2019]) this will likely serves the primary purpose of producing advanced biofuels, for approx. 160 – 255 Mtoe [Imperial College London Consultants, 2021]. Though of limited relevance for Europe, the controlled combustion of rice husk produces a material – similar to pozzolana - of interest for the production of cement [Chatham House, 2018].

4.2.3 Municipal and industrial wastes

Co-processing waste and industrial by-products in a cement plant maximises their potential, i.e. by extracting the energy potential and using what remains as a raw material [Cembureau, 2013]. In 2019, the European cement industry recycled over 14 million tonnes of slag; over 3 million tonnes of fly ash; and sourced 32% of its energy from alternative fossil and mixed wastes such as plastics, industrial waste or tyres [GCCA, 2019].

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(6) https://www.thisisukconcrete.co.uk/Perspectives/World-first-UK-hydrogen-trials-demonstrate-pathway.aspx

Table 5 Share of fuel category in total thermal energy and share of fuel in fuel category (%)

Fuel	**EU27**	**Global**
Fossil fuel	**51%**	**81%**
Coal + anthracite + waste coal (%)	27%	46%
Pet coke (%)	62%	41%
(ultra) Heavy fuel (%)	1%	1%
Diesel oil (%)	0%	0%
Natural gas (%)	1%	10%
Shale (%)	1%	0%
Lignite (%)	9%	2%
Alternative fossil and mixed wastes	**32%**	**12%**
Waste oil (%)	2%	4%
Tyres (%)	12%	16%
Plastics (%)	51%	39%
Solvents (%)	5%	9%
Impregnated saw dust (%)	2%	1%
Mixed industrial waste (%)	19%	18%
Other fossil based wastes (%)	8%	13%
Biomass	**17%**	**7%**
Dried sewage sludge (%)	14%	9%
Wood, non impregnated saw dust (%)	18%	22%
Paper, carton (%)	1%	1%
Animal meal (%)	49%	13%
Animal bone meal (%)	2%	1%
Animal fat (%)	0%	0%
Agricultural, organic, diaper waste, charcoal (%)	3%	40%
Other biomass (%)	13%	15%

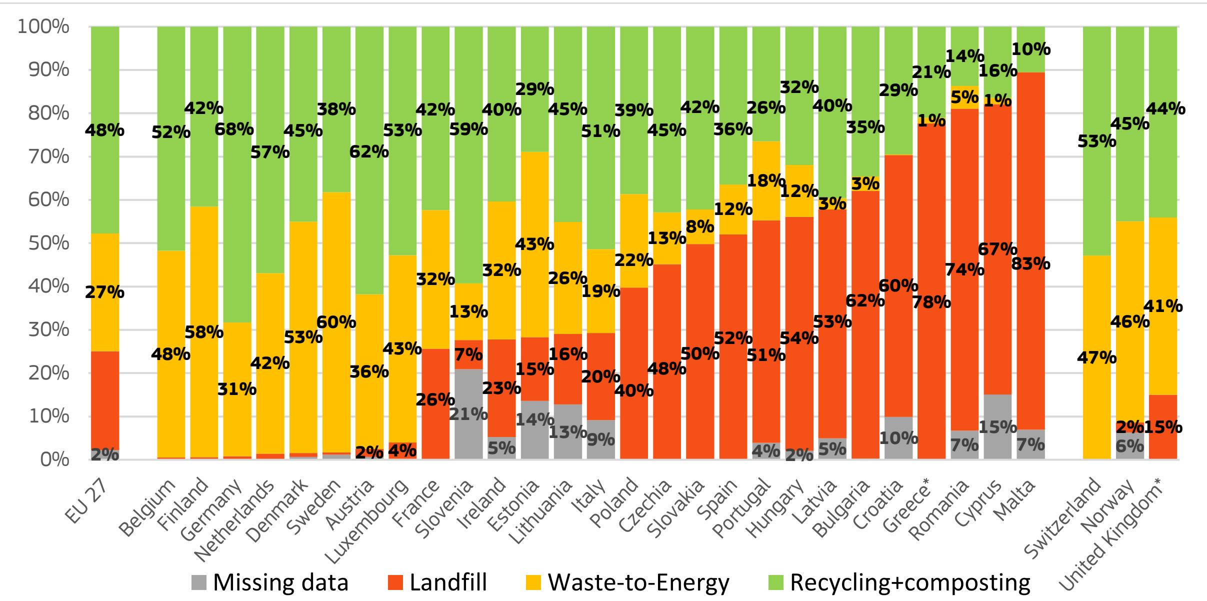
Source: JRC based on [GCCA, 2019]

The generic notion of waste entails different categories such as refuse derived fuel (RDF); municipal solid waste (MSW); commercial and industrial waste (C&IW); construction and demolition waste (CDW) and solid recovered fuel (SRF) [ECRA, 2016]. Further waste may be labelled as renewable, should it contain biological material [Eurostat, 2019]. For an extended list of wastes considered as fuel for the cement industry, refer to [European Commission, 2013b; GCCA, 2019]. [IFC, 2017] provides techno-economic and environmental details on each waste in cement industry, while net calorific values are available from multiple sources [IIPNetwork, 2014; ECRA, 2016].

In middle- and low-income countries, processing waste in cement plants instead of (too frequent) landfilling could reduce emissions without investing in waste-to-energy plants [Khan et al., 2020]. In Europe, incinerators with a capacity lower than 20 MW were not covered by the ETS, as waste treatment served an environmental purpose against landfilling. This may change [EP, 2022] possibly enhancing waste prevention and recycling but certainly increasing the cost of incineration [CEDelft, 2021]. As such, alternative fuels in cement production could substitute 30% of fossil fuels in developing regions and 70% in developed regions by 2050 [ECRA & WBCSD/CSI, 2017], especially building up on collaboration between the cement [Schenckprocess, 2022] and the waste treatment industry [STADLER, 2021] at local level.

In 2020, EU27 households produced over 230 million tonnes of municipal waste [Eurostat, 2020], which are handled differently across European countries (**Figure 28**). Discarding recycling and landfilling of municipal wastes while adding additional waste streams (i.e. commercial and industrial wastes), EU28 waste treatment plants treated over 90 million tonnes of waste in 2018 [CEWEP, 2020]. This excludes about 11Mt of waste treated through co-incineration [Prognos, 2018]. Looking forward, about 140 Mt of waste could be treated by waste-to-energy in 2035 [Prognos, 2018]. In this context, the role of cement in co-incineration may be reinforced: Co-incineration takes place in coal fired plants and in cement kilns. Yet the share of cement kiln in co-incineration by 2035 is reinforced in projection 2 ("Potentials", assuming with more ambitious CO_2-emissions legislation) versus baseline ("status quo") and projection 1 ("Implementation of current legislation") scenarios [Prognos & CE Delft, 2022].

Figure 28 Municipal waste treatment, 2020



Source: [CEWEP, 2022]

Though associated with coal production [ETH, 2018], bottom ash is also a product of waste-to-energy plant. The 96 million tonnes of waste treated in Waste-to-Energy plants in Europe in 2018 led to the production of approximately 19 million tonnes of bottom ash. Such ashes contain about 80 to 85% of mineral and are already used as cement substitutes [CEWEP, 2018]. Research investigates the development of new cement based on processed incineration ash from Municipal Waste Incinerators [ASH-CEM, 2016] and piloting: the treatment of 90 kt of bottom ash from 450 kt municipal waste yields 30 kt of raw material for clinker [INDAVER project, 2022].

Next to fossil fuel substitution, up to 5% of primary raw material in clinker can be replaced by mineral ashes contained in waste. This saves primary raw materials for cement production and avoids landfilling of minerals [ECOFYS, 2016]. While the organic content provides thermal energy, the non-organic content provides minerals. The share of non-organic content reaches up to 45% in case of waste water sludge; 25% for tyres and 13% for municipal waste [ECRA, 2016].

Substituting fossil fuel by waste has consequences: The quality of waste should be suitable to the cement plants for co processing: High moisture and chlorine and high percentage of heavy metals are not acceptable [CMA & IIP, 2016]. Chlorine deposition does deteriorate the stable operation of the kiln; while trace elements impair clinker quality and impact the environment. Waste is therefore pre-treated, also in view of enhancing its combustion (i.e. dried and shredded or gasified) [ECRA, 2016]. [IFC, 2017] provides an overview of pre-treatment technologies.

Among the various types of waste, plastic is worth looking at. Plastic is the second most used fuel in the EU cement industry in 2019, representing over 16% of the thermal energy consumed [GCCA, 2019]. Statistics on plastic recycling, energy recovery and landfilling between 2006 and 2018 highlight the downward trend of landfilling and upward trends of recycling and energy recovery. Looking backwards, 42% of waste plastic has been handled by energy recovery in 2018, following an annual growth of 4.9% since 2006 [PlasticEurope, 2019]. Looking forward, two scenarios (focusing on circularity, thus recycling) indicate the evolution of the plastic market by 2050: emissions from production and end-of-life of plastic may increase from 732 $MtCO_2$/year in 2018 to 919 $MtCO_2$/year in 2050 [ETC, 2018]; Energy recovery from plastic waste is foreseen to increase, from 15% of the 49 Mt plastic produced in the EU in 2017, to 21% of 61.6 Mt in 2050 [SITRA, 2018]. Plastic circularity comes at a cost, though: A plastic sorting plant is expected to address Sweden's plastic package recycling needs as of 2023, following an investment of SEK 260 million [Fossil Free Sweden, 2020].

4.2.4 Electrification

Around 52% of the European process industries' own emissions originate from the use of fossil fuels for heating purposes. Based on GHG emission-free electricity, electric kilns could reduce the emissions of the cement and lime sector by around one-third [A.Spire, 2020]. Electric kiln is assumed to be the most energy efficient with specific energy intensity – 2.68 GJ/t clinker, which is lower than the most efficient dry kiln [Dhas, S., 2021]. By reducing the volume of emissions and improving on exhaust quality compared to (fossil) fuel combustion, carbon capture could be eased. [Agora Energiewende and Wuppertal Institute, 2021].

Technologies for high temperatures based on electricity include plasma; electrical flow heaters; microwave heating; resistive electrical heating; induction heating [Cembureau, 2020b; CemZero project, 2018; Hodges & Woods, 2020] yet they are still in development and require further investigation [Sandalow et al., 2019; Global Cement, 2022]. Electric kilns will be developed in stages, with research programmes for enabling topics laying the foundation [A.Spire, 2020] and public investment in research and development [Hasanbeigi et al., 2021]. EU projects, instrumental towards this objective, include CemZero [CemZero project, 2018]; LEILAC [LEILAC project, 2016; Agora Energiewende and Wuppertal Institute, 2021]; LEILAC2 [LEILAC2 description, 2020; HeidelbergCement, 2021]; and Decarbonate [Decarbonate project, 2022]. ELSE in Norway or the early demonstration stage for plasma torches in clinker manufacture in the UK [Hodges & Woods, 2020] are also contributing to knowledge creation on this topics.

Technology for clinker sintering include Coolbrook Roto Dynamic Heater (foreseen for installation in Mexico and India, and for commercial use at industrial scale in 2024 [Global Cement Magazine, 2022]) and SaltX electric plasma heating (process which has been tested in a pilot plant [SaltX Technology, 2022]). Through the LEILAC project, market readiness of CO_2 capture in combination with **electrification of the high temperature heat at the calciner** can be reached as early as 2025 [Agora Energiewende and Wuppertal Institute, 2021]. Extending electrification will take more time, reaching Technology Readiness Level (TRL) 9 in 2035 [A.Spire, 2020], possibly playing a role by 2040 [GCCA, 2021] if already commercially ready by then [ETC, 2018]. Indeed strategic decisions add-up to the technical and economic feasibility: Technical challenges lay in the required changes in industrial equipment [Sandalow et al., 2019]. These result in costs, possibly higher for upgrading existing plants than building new capacities in case of increased demand [ETC, 2018]. And while the electrification of basic materials production may well be technically possible, this would impact both the industry and the energy sector through their physical (supply and demand) and economic (prices) interactions [Lechtenböhmer et al., 2016]. This therefore drives the installation of renewable energy capacity connected to cement production sites, mostly solar electricity [Cimpor, 2021a; Cimpor, 2021b; Górażdże, 2021; Vassiliko Cement, 2020; Votorantim Cimentos, 2021], though wind electricity is also relevant [Opterra, 2022].

4.2.5 Renewable energy and hydrogen

Other vectors of low carbon high temperature are solar energy [Heliogen, 2019; SOLPart project, 2016; Synhelion, 2022] and hydrogen [Cembureau, 2020c; CEMEX, 2021; CEMEX, 2022b; HeidelbergCement, 2020; NewClimate, 2020; NGHV project, 2022; GCCA, 2021; SolCement project, 2021], though hydrogen may not be suitable as a single source of heat for the kiln operation [MPA, Cinar Ltd & VDZ GmbH, 2019]. It is worth noting the EUR 60 million H2CEM project [Titan, 2022], funded under the EUR 5.2 billion Important Project of Common European Interest Hy2Use [European Commission, 2022d]. H2CEM foresees the production and use of hydrogen in three Greek cement plants and the construction of a pilot rotary kiln, primarily fuelled with hydrogen. More on hydrogen can be found in the CCUS section 4.4 of this report, possibly enabling oxycombustion (when hydrogen and oxygen are co-produced by hydrolysis), or the production of chemical feedstock (when CO_2 is combined into chemicals with added value).

4.3 Alternative cements and/or materials

While **Portland cement** is the reference, alternative cement compositions have been and are being developed. Drivers are availability of alternative raw materials and needs of specific applications, though the carbon intensity of Portland cement is also playing a role, striving to reduce the content of carbonate in the raw meal (contributing to process emissions) and the temperature of the thermal process (contributing to emissions through fuel combustion). Mechanical properties of such alternative cements should however not be compromised. So the setting and hardening processes are key elements in the identification of suitable low-carbon cements.

Hydraulic cements harden through chemical reactions between cement and water, creating hydrates which are not soluble in water. During this process more than 70 different crystals evolve in the hardening of cement [The Graphene Council, 2021]. **Non-hydraulic cements** harden through carbonation reactions with CO_2 [Climate Strategies, 2014]. This approach reverses the calcination of carbonates by mineralising CO_2 and is therefore of interest also towards CO_2 capture and decarbonisation efforts. Carbonation also affects Portland clinker and the products of its hydration (such as calcium hydroxide and calcium silicate hydrate) [Ylmén & Jäglid, 2013]. As such, carbonation may follow hydration. In addition, **pozzolanic materials** do not harden by themselves when mixed with water. Yet, they react at normal ambient temperature, when finely ground and in the presence of water, with dissolved calcium hydroxide ($Ca(OH)_2$) to form strength developing calcium silicate and calcium aluminate compounds [EN 197-1, 2011].

Irrespectively of the approach used, the reactions should lead to physically and chemically stable concretes across their (as long as possible) lifetime and (as broad as possible) operating conditions. This implies, but is not limited to, the formation of hydrates and/or carbonates with low water solubility and high thermal stability (preserving the set concrete from water damage, chemical decomposition or strains from changes). For the end-result to be of quality, these aspects also need to be considered during the curing process, i.e. ensuring physical and chemical stability of the concrete structures through their hardening.

For these hydration and/or carbonation reactions to take place, the right constituents (mineral phases) should be mixed in the right conditions (stoichiometry, also with reactant (be it water and/or CO_2), temperatures, etc…), awaiting for the reactions to unfold. This study reviews cements (standardised cements in Europe or not) and their main mineral phases prone to react towards hardened chemicals (**Table 6**). The objective is to discuss alternative sourcing of such mineral phases and/or precursors, in view of identifying cement production pathways that may be less CO_2 intensive than current Portland cement production.

4.3.1 Review of cements and reactive phases

This section recalls existing cements, their cementitious phases and their principal hardening process, referring to the following cement notation: C = CaO; SiO_2 = S; Al_2O_3 = A; Fe_2O_3 = F; SO_3 = $; H_2O = H). Cement chemistries are described in three European standards:

— "**Common cements**" are defined in six classes (CEM I to CEM VI) by standard EN 197. All common cements contain Portland clinker (though in various concentrations) which hardens through the reaction of mainly four phases (alite; belite; tricalcium aluminate, and tetracalcium aluminoferrite). The silicate phases (alite – C_3S and belite – C_2S) hydrate in calcium silicate hydrate (C–S–H) and calcium oxide (CH). The aluminate phases (tricalcium aluminate – C_3A and tetracalcium aluminoferrite - C_4AF) hydrate in ettringite, while consuming sulfate provided by gypsum [Cadix & James, 2022]. Further, depending on the cement class covered by standard EN 197, Portland clinker may be substituted by different materials as indicated in section 4.3.2.

— “**Calcium aluminous cement**” (CAC) is defined by standard EN 14647. The main component of CAC is monocalcium aluminate. Other mineralogical compounds include calcium alumino-ferrites, dicalcium silicate, and calcium silico-aluminate or gehlenite. Hydraulic hardening of calcium aluminate cement is primarily due to the hydration of monocalcium aluminate towards the only stable cubic C_3AH_6 phase [EN 14647, 2005];

— “**Supersulfated cement**” is defined by standard EN 15743. Its main constituent is granulated blast furnace slag (GBFS). GBFS consists of at least two-thirds by mass of the sum of calcium oxide, magnesium oxide and silicon dioxide. The remainder shall be aluminium oxide together with small amounts of other compounds. Supersulfated cement hardens providing that hydraulicity of granulated blast furnace slag is activated by calcium sulfate or Portland cement. Hydration of calcium sulphate and of Portland cement leads to calcium hydroxide (Portlandite or $Ca(OH)_2$), which then combines with the slag oxides to create additional (C-S-H) material [EN 15743, 2015; Pal et al., 2003]. It is worth noting the overlap between supersulfated cement defined in EN 15743, which contain at least 90% of GBFS and CEM III/C cement, from EN 197, which contains 81 to 95% of GBFS.

Alternative cement chemistries are readily available or subject to research and development [ISAL, 2021]:

— **Reactive belite cement** contains the same four phases than Portland cement, though in different proportions. Produced as common cements, though at lower sintering temperature, this favours the belite phase over the alite phase and reduces the resulting emissions.

— **Calcium sulfoaluminate cement** (CSA) is a type of cement largely used in China. This type of cement has variable compositions, but all of them contain ye’elimite (also known as calcium sulfoaluminate, with a proportion of 5 to 70% in the CSA clinker) and other minor phases (such as C_2S, CA, C_4AF, and C$) [Kleib et al., 2021b]. With calcium sulfate (anhydrite, $CaSO_2$ or C$), ye’elimite will hydrate in ettringite, while the absence of calcium sulfate leads to calcium aluminate monosulfate ($C_4A\$H_{12}$) [Zajac et al., 2019].

— **Belite-ye’elimite-ferrite cement** (BYF or BCSA) contains ye’elimite in addition to belite and tetracalcium aluminoferrite.

— **Carbonatable calcium silicate cement** (CCSC) clinker contains mostly wollastonite, but also calcium aluminate and rankinite. Both wollastonite and rankinite carbonate into calcium carbonate [Sahu & Meininger, 2019].

— **Magnesium oxides derived from magnesium silicates** (MOMS) cement clinker is usually composed of magnesium oxysulfate, which forms a magnesium carbonate phase after carbonation [Ba et al., 2019].

The above mentioned phases and their principal hardening process is summarised in the following table (**Table 6**), referring to the following cement notation: C = CaO; SiO_2 = S; Al_2O_3 = A; Fe_2O_3 = F; SO_3 = $; H_2O = H).

Table 6 Overview of cement hardening phases

Phases name and notation	Chemical composition	Cement	Reaction	Product
alite; C_3S	$3CaO{\cdot}SiO_2$	OPC	Hydration	calcium silicate hydrate (C-S-H)
belite; C_2S	$2CaO{\cdot}SiO_2$	OPC	Hydration	calcium silicate hydrate (C-S-H)
tricalcium aluminate; C_3A	$3CaO{\cdot}Al_2O_3$	OPC	Hydration with sulphate	ettringite ($C_6A\$_3H_{32}$)
tetracalcium aluminoferrite; C_4AF	$4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$	OPC	Hydration with sulphate	ettringite ($C_6A\$_3H_{32}$)
monocalcium aluminate; CA	$CaO{\cdot}Al_2O_3$	CA	Hydration	tricalcium aluminate hexahydrate (C_3AH_6)
Granulated blastfurnace slag	calcium oxide (CaO), magnesium oxide (MgO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) + other compounds.	SSC	Hydration with sulphate or Portland cement	calcium silicate hydrate (C-S-H)
ye'elimite or calcium sulfoaluminate; $C_4A_3\$$	$4CaO{\cdot}3Al_2O_3\ SO_3$	CSA	Hydration	calcium aluminate monosulfate ($C_4A\$H_{12}$)
			Hydration with sulphate	ettringite ($C_6A\$_3H_{32}$)
calcium silicate hydrate (C-S-H)	$3CaO\ 2SiO_2\ 4H_2O$	Hydrated	Carbonation	calcium carbonate ($CaCO_3$)
calcium hydroxide; CH	$Ca(OH)_2$	Hydrated	Carbonation	calcium carbonate ($CaCO_3$)
calcium silicate or wollastonite; CS	$CaO{\cdot}SiO_2$	CCSC	Carbonation	calcium carbonate ($CaCO_3$)
rankinite; C_3S_2	$3CaO{\cdot}2SiO_2$	CCSC	Carbonation	calcium carbonate ($CaCO_3$)
magnesium oxysulfate	$3Mg(OH)_2{\cdot}MgSO_4{\cdot}8H_2O$	MOMS	Carbonation	magnesium carbonate ($MgCO_3$)

Source: JRC.

4.3.2 Substitute materials to Portland clinker and their activation methods

Standard EN 197 foresees the addition of constituents (besides Portland clinker and minor additional constituents such as Gypsum). These constituents partially replace clinker in Portland cement thus saving both energy-related and embodied CO_2 emissions. They are referred to as supplementary cementitious materials:

— **Granulated blast furnace slag** shall consist of at least two-thirds by mass of the sum of calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO_2);

— **Pozzolanas** consist essentially of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). The remainder contains iron oxide (Fe_2O_3) and other oxides. Silica fume and Fly ash are pozzolanic materials;

— **Silica fume** consists of very fine spherical particles containing at least 85% by mass of amorphous silicon dioxide (SiO_2);

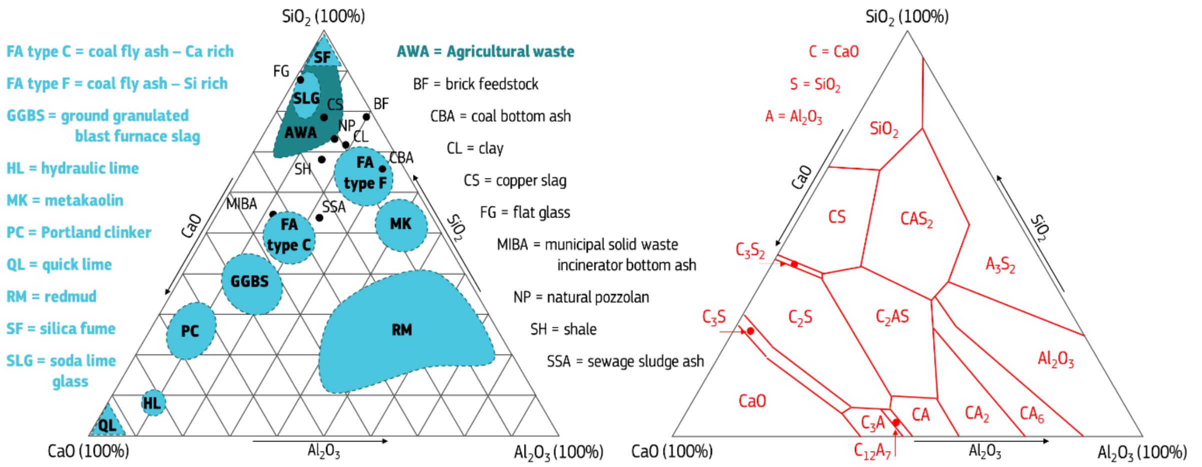
— **Fly ash** mainly consists of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). The remainder contains iron oxide (Fe_2O_3) and other compounds. Depending on the proportion of reactive calcium oxide (CaO), fly ash are deemed siliceous (CaO < 10% by mass) or calcareous (CaO > 10% by mass). In addition to pozzolanic properties, calcareous fly ash also display hydraulic properties.

— **Burnt shale** contains clinker phases, mainly dicalcium silicate (belite) and monocalcium aluminate (CA). It also contains, besides small amounts of free calcium oxide (CaO) and calcium sulfate (C$), larger proportions of pozzolanically reacting oxides, especially silicon dioxide (SiO_2). Consequently, in a finely ground state burnt shale shows pronounced hydraulic properties like Portland cement and in addition pozzolanic properties.

— **Limestone** is mainly composed of calcium carbonate which, when finely ground, displays properties beneficial to the cement and concrete [GCCA, 2022].

Most reactive phases are the result of combinations between calcium, aluminium and silicon oxides. **Figure 29** summarises different raw materials providing the suitable chemical mix and cement phases. It is **worth noting the technical possibility to use raw materials that are not (yet) explicitly referred to in standards.**

Figure 29 Raw materials (left) and cement phases (right) in the calcium oxide, aluminium oxide and silicon oxide system



Source: JRC, based on [Novak, T., 2022] & [Taylor, H. F. W., 2007]

For a specific (hydration or carbonation) reaction to take place, material reactivity needs to be enhanced. Hydration [ECRA & WBCSD/CSI, 2017] and carbonation [Wang et al., 2021] reactions can be enhanced, along (a mix of) activation approaches depicted in **Table 7**. Comminution and chemical activation are the most common methods, especially used for common cements.

Table 7 Review of activation methods

Method	**Technological features**	**Advantages**	**Disadvantages**
Chem. additives	Modification of formulations	Wide range of modified formulations	High price
Addition of surface active substances	Formation of additional crystallisation centres and stimulation of growth of neoplasms of secondary generation	Compaction of cement stone structure	Limited range of applications
Grinding of binder by a mill	Different types of mills—ball, vibratory, vario-planetary, etc.	Simplicity	High energy costs
Liquid-phase mechano activation	The mechanical effect produced by rotary-pulsating apparatus	Hydration occurs more fully and the mobility of the concrete mix increases	Small amount of the mixture charge per cycle
Magnetic activation of mixing water	Cycle magnetic water treatment	Energy efficiency	Expensive equipment
Hydro dynamic activation	Synergistically used are the physical and chemical processes occurring in the water flow: aeration, cavitation (cold boiling), collapsing, coagulation	Transfer of dissolved substances in water into insoluble substances and their removal	Relatively low efficiency
High-voltage electrical discharge treatment	The imposition on a water-cement system of a constant field of high intensity leads to phenomena of electrolysis of water and electrophoresis, i.e. of the motion of charged particles in an electric field	Significant change in the ion composition of the suspension and the appearance in the water of polarized groups	Technological complexity
Electro physical activation	Electromagnetic action (sometimes followed by steaming)	Improvement in elastic strength of concrete	High costs
Microwave (dielectric) heating	The absorption by the material the energy of the electromagnetic fields of the high-frequency or microwave range and the conversion of this energy to thermal	High speed of technological process	Expensive equipment
Thermal activation	Heating with subsequent cooling according to various schemes	A relatively simple and effective way	High costs
Ultrasonic treatment	Ultrasonic treatment causes the effect of cavitation, grinding of solid particles, micro cracks in crystals	Intensification of cement hydration processes	High energy costs
Thermo acoustic activation	The cement paste is pre-treated in an aerohydrodynamic activator, followed by stirring with aggregates and heating before laying at 60–65°C.	Strength increase 1.5 times	Complexity of processing

Hydration reactions can lead to different products depending on the presence or absence of readily available sulphate ions.

Source: [Fediuk et al., 2018].

4.3.3 Investigation towards low-carbon cements

Following the overview of known mineralogical phases that can hydrate and carbonate and develop and strength bearing products and raw materials that lead to such active phases, the next section will focus on identifying combinations of raw materials and activation methods for innovative and potentially low-carbon cements. Along the standardisation approach, careful testing of alternative raw materials used in the clinker production process is required [ECRA & WBCSD/CSI, 2017].

Following a USD 0.5 million grant for research [ARPA-E, 2020], Brimstone (US) received USD 55 million for the construction of a pilot plant, which aims to produce Portland cement from calcium silicate rock, in place of calcium carbonates [CNBC, 2022]. Calcium silicate clinker can also be manufactured through an alternative process (i.e. without a kiln): pre-hydrated calcium silicate compound (α-C2SH) can be produced in autoclave and activated by intergrinding (silica-rich) materials [ECRA & WBCSD/CSI, 2017], such as celitement or heating at low temperatures [UNEP, 2017].

Similarly to granulated blast furnace slag, fly ash and silica fume, wastes of thermal processes are likely to contain de-carbonated minerals. Pozzolanas are naturally occurring materials, readily available underground [ETH, 2018] or in biomass waste (e.g. rice husk). However, pozzolanas require activation by thermal treatment before they can be used as clinker replacement [ECRA & WBCSD/CSI, 2017]. As pozzolanas, calcined clays may be incorporated into blended cements, under standard EN 197-1 [ONESTONE CONSULTING LTD., 2021], such as and Materrup MCC1 cement [Materrup, 2022]. Calcined clays are also investigated by Vicat [FLSmidth, 2021b]. The adoption of EN 197-5 in May 2021, enables higher use of pozzolana (i.e. ranging between 36% to 50% of cement composition) [EN 197-5, 2021], such as Cementir FUTURECEM cement [Cementirholding, 2022]. Yet there is even potential for cements (like Crosslinked Clay Cement) with up to 70% raw clay [Materrup, 2022].

Geopolymers are a clinker-free alternative to cement. Geopolymers are the result of a reaction between solid aluminosilicate materials (such as fly ash, GBFS, or naturally occurring metakaolin) and an alkaline solution (such as sodium silicate). Most of the emissions come from the production of the alkaline solution: Either through the carbonation of sodium carbonate or for the electrolysis of salt, the latter being possibly decarbonised through renewable energy [BZE, 2017; ECRA & WBCSD/CSI, 2017; ETH, 2018; Singh et al., 2020]. Since fly ash and GBS can already be incorporated into Portland cement, decarbonisation benefits seem limited. However the European Regional Development Fund (ERDF) funded project REINCE aims at developing geopolymers from materials with limited uses [Cementos Cruz, 2022], such as waste materials from pulp industry [CICECO, 2019]. In addition to supersulfated cement, based on slag, Hoffmann Green Cement (FR) is commercialising alkali activated cements. The construction of its second plant (H2) required an investment of EUR 22 million. This plant is expected to product 250 kt clinker-free cement per year from 2023 [Hoffmann Green Cement, 2022], and a third production plant is already planned for 2024 [Hoffmann Green Cement, 2022b].

4.3.4 Carbon negative cements

Most emissions in current cement production stem from the calcination of limestone (calcium carbonate) in calcium oxide for the production of clinker: Reducing the share of limestone as raw material for clinker production does reduce CO_2 emissions. Further, cement curing through carbonation processes serve as CO_2 sink throughout the material lifetime. By enhancing and combining the two approaches (developing alternatives to Portland clinker that may sequester CO_2), carbon capture may exceed CO_2 emissions over the cement lifetime, thereby defining carbon-negative cement [Chatham House, 2018]. Such cements hold potential to make a significant contribution to the fight against climate change. However promising, these cements are not yet ready to be commercialised and require further research [BZE, 2017] since processes are still at low Technology Readiness Levels [Rootzén, J., 2015]. This approach to zero-carbon cement may play a role only at a later stage compared to geopolymer cements, reducing the use of clinker, mineral carbonation and reducing the use of cement [BZE, 2017], though research is ongoing: German project K4 aims, on one hand, to develop low-calcium clinker from recycled cement paste, thereby reducing the requirement for limestone; And, on the other hand, to develop a new type of curing process through the capture of carbon dioxide [K4 project, 2022].

Carbonation of Portland clinker-based concretes is naturally occurring (see section 4.3.1) and can be enhanced, though this remains complex to implement and with minimal CO_2 consumption. Though it further hardens concrete, it lowers its pH thus threatening steel reinforcements. Special carbonatable calcium silicate clinkers (CCSC) are more effective at capturing CO_2 and less CO_2 intensive in their production, yet their low reactivity prevents hardening by hydration. Another avenue focuses on hydraulic cements based on magnesium oxide from magnesium silicates. Such MgO-based clinkers can be made using ultramafic rocks (composed of magnesium silicates and rich in basic MgO) instead of limestone. This avoids CO_2 emissions from limestone calcination while enabling CO_2 capture as magnesium carbonates [UNEP, 2017]. Provided that mineralisation is eligible for ETS credits, this approach may even be economical [Strunge et al., 2022].

4.4 Carbon Capture, Utilisation & Storage

Implementing the vision for a low carbon society requires among other measures, accelerated development and deployment of CO_2 emissions reduction options [IEA & WBCSD/CSI, 2018]. CCUS) is seen as a promising solution to address cement CO_2 emissions from cement production. The International Energy Agency (IEA) identifies the integration of emerging and innovative technologies, like carbon capture, to provide the largest cumulative CO_2 emissions reductions: the reduction reaches 48% by 2050 in the 2 Degrees Celsius (2DS) scenario in comparison to the Reference Technology Scenario (RTS). The policy scenarios on the impact assessment of the European Commission's Climate Target Plan achieve reductions on the industrial sector ranging between 88% and 93% compared to 2015. A major part of the reductions in 2050 is due to technologies such as clean gases and carbon capture and storage and carbon removals, including CCUS technologies and CO_2 storage in materials [European Commission, 2020c]. However, no specific information on the cement sector is available.

Emission mitigation is hampered by the different origins of emissions (calcination of limestone and fuel combustion for thermal processes). It may be easier and/or cheaper to address emissions after their production than to eliminate or even mitigate the different sources of emissions independently, thereby making case for CO_2 capture and storage. Several steps are needed for this approach to successfully prevent CO_2 release in the atmosphere: CO_2 needs to be captured where it is produced (in this case a cement plant) and it needs to be transported to a facility for handling (i.e. either for its storage or for its transformation and further use). With developments happening across the globe [Plaza et al., 2020], this section focuses on European progresses: **Table 8** summarises efforts towards CO_2 capture, directly impacting the cement production, providing a description of the relevant technologies and of their application; CO_2 transport and handling are also highlighted, when applicable to an ongoing CCUS project in the EU cement industry; while **Table 10** summarises progresses towards CO_2 utilisation following capture and transport.

4.4.1 Carbon capture technologies

While CO_2 capture is technically feasible, large scale roll-out remains to happen to effectively contribute to climate change. Various approaches and even more technologies are being developed [GlobalCCSInstitute, 2021], though only a subset is investigated in approx. 20 EU cement plants (**Table 8**). Due to emissions from the calcination of limestone, the cement industry displays high CO_2 concentration in exhaust gases, higher than in the power generation sector. This strengthens the case for carbon capture in this industry.

Within the ConsenCUS project (2021-2025), Cementir will test from 2023 a demonstration plant at Aalborg (DK). Carbon capture will rely on **alkali absorption**, coupled to a novel electrodialysis cell to capture up to 100 kgCO_2/hour. The objective is to reach TRL 7 [ConsenSUS project, 2021].

The CLEANKER project (2017-2021) demonstrated **calcium looping** at Buzzi Unicem's plant in Vernasca (IT) [CLEANKER description, 2017; CLEANKER project, 2017]. In the frame of the ANICA project (2019-2022), Dyckerhoff will rely on the indirectly heated carbonate looping (IHCal) process to capture CO_2 at its Göllheim (DE) plant, striving to reach TRL 6 [ANICA, 2022]. Calcium (and chemical) looping technologies involve oxides in carbonation and calcination processes to concentrate CO_2 emissions, while indirect heating is another approach to CO_2 capture described below.

With the ACCSESS project (2021-2025), HeidelbergCement aims to demonstrate at TRL 7 CO_2 capture with **enzyme**-based post combustion capture technology along three axis: Integrate Saipem solvent (7) technology; pilot Saipem solvent combination with Prospin Rotating Packed Bed technology (8) at Górazdze (PL) cement plant; and use of Linde (9) amine based post-combustion capture technology at Hanover (DE) facility [ACCSESS description, 2021; ACCSESS project, 2021].

Technology based on Iolitec (10) **ionic liquid** are being developed and tested at Titan's Kamari (HE) facility in the frame of the RECODE project (2017-2022), with the objective to increase to TRL 6 [RECODE description, 2017; RECODE project, 2017].

Technology relying on **amine scrubbing** is being implemented at Mannersdorf (AT) site (operated by Lafarge) in the frame of the Carbon2ProductAustria project. The objective is to capture 10 ktCO_2/year. To this end, CO_2 is dissolved in the amine solvent in the absorber tower and released in the desorber tower. Once the steam is condensed, exhaust is composed of pure CO_2 (>95 wt.-% CO_2) [C2PAT, 2022].

Solvent technology is also mobilised in Carbon Clean APBS-CDRMax technology, in which **Amine-Promoted Buffer Salts** (APBS) extract CO_2 from the flue gas of industrial plants

(7) https://www.saipem.com/en/solutions/renewables/carbon-capture
(8) https://www.rpb-prospin.com/products
(9) https://www.linde-engineering.com/en/process-plants/co2-plants/carbon-capture/post-combustion-capture/index.html
(10) https://iolitec.de/technology/energy-cleantech/co2-capture

[Carbon Clean, 2022]. This technology is being implemented at Holcim's Carboneras (ES) plant for capturing 10% of CO_2 emissions from 2022 [LafargeHolcim & Carbon Clean, 2021]. Further a feasibility study indicates the possibility for this technology to capture 100 tCO_2/day at Rüdersdorf (DE) with the possibility to be ramped up to 2 kt/day providing funding is made available [Carbon Clean & CEMEX, 2021].

Hereon's PolyActive **membrane** [Brinkmann et al., 2022] is being tested at Holcim's Höver (DE) site. The objective is to capture 5.6 $ktCO_2$ in 2023 to 1.3 $MtCO_2$ from 2026 [Holcim & Cool Planet, 2021].

Cryogenic separation and membrane technology are mobilised in Air Liquide installation relying on Cryocap technology ([11]). This includes Holcim's Kujawy (PL) and Eqiom's Lumbres (FR) sites. It is **worth noting that the latter plant received funding through the EU Innovation Fund K6 project** [Eqiom, 2022].

The approaches towards CO_2 capture described above rely on separation processes. However oxyfuel combustion and indirect heating for the calcination of limestone do also deliver exhaust gas with high CO_2 content, ready for further handling.

LEILAC1 (2016-2021) and LEILAC2 (2020-2025), implemented at HeidelbergCement sites of Lixhe (BE) and Hanover (DE), rely on Calix technology ([12]) for the carbon capture by direct separation through **indirect heating** and calcination of limestone [LEILAC project, 2021]. In this approach, limestone is finely grinded. This powder is then briefly heated in a specifically designed reactor. Limestone calcination and fuel combustion take place in separate chambers, allowing for distinct exits of exhaust gases. Exhaust gas of the calcination chamber display a high CO_2 purity. And this technology is compatible with electrification, possibly decarbonised by the use of renewable energy.

Injecting pure oxygen, in place of air, in the kiln improves combustion and – by removing nitrogen - increases CO_2 concentration in exhaust gas. Pure oxygen can be sourced in different ways, though large quantities are needed [ECRA, 2016b]. This approach, called **oxyfuel or oxy-combustion** is currently tested at various cement production sites:

- A 330 MW electrolyser for hydrogen production is being planned for 2023 close to Vicat's Montalieu-Vercieu (FR) plant. The decomposition of water into hydrogen will provide oxygen required by the cement plant oxycombustion.
- Oxyfuel technology is also tested at LafargeHolcim site Lägerdorf (DE). Westkueste100 project investigated the feasibility study for conversion to an oxyfuel process for the production of synthetic hydrocarbon [Westkueste100, 2019] while Carbon2Business project is implemented a 2nd generation oxyfuel process, aiming to capture over 1 $MtCO_2$ annually [Holcim, 2022c].
- In the frame of the CEMCAP project, Hanover (DE) site of HeidelbergCement has been used for the design of a full demonstration plant (TRL 7) based on oxyfuel [CEMCAP project WP9, 2018]. This site is also the location for the LEILAC2 project, which aims at concentrating CO_2 in the exhausts gas of the calciner. The CEMCAP project also looks

([11]) https://www.engineering-airliquide.com/fr/cryocap-h2-separation-cryogenique-du-co2
([12]) https://calix.global/our-technology/

into chilled ammonia process; membrane-assisted CO_2 liquefaction; and calcium looping (CaL) capture, advancing the former technology to TRL 6 [CEMCAP project, 2018].

- Supported by four European cement producers, gathered in the Cement Innovation for Climate consortium, Schwenk's Mergelstetten (DE) site is operating a demonstration plant based on Polysius Pure Oxyfuel ([13]) technology [Catch4climate, 2021; Catch4climate, 2021b; Catch4climate, 2022], with a capacity of 450 t/day [UVP-Verbund, 2022].
- The ongoing upgrade of Holcim's Obourg plant (BE) is foreseen to include oxycombustion technology [Holcim, 2021b; Holcim, 2022]. Along the same line, HeidelbergCement's Colleferro (IT) and Holcim's Retznei (AT), sites have been selected for ECRA's research project on CCS [CCUS projects network, 2019; ECRA, 2018].

([13]) https://insights.thyssenkrupp-industrial-solutions.com/story/polysiusr-pure-oxyfuel-best-in-class-technology-for-carbon-capture-in-cement-production/

Table 8 CO_2 capture projects in the EU cement industry

Country	Plant	Company	Technology	More info
Austria	Mannersdorf	Lafarge	Amine scrubbing in full-scale plant by 2030	Carbon2ProductAustria project
Austria	Retznei	Holcim	Design of oxyfuel kiln	ECRA research project
Belgium	Lixhe	HeidelbergCement	Pilot plant for indirect heating	LEILAC1 (2016-2021)
Belgium	Obourg	Holcim	Plans for oxyfuel technology by 2029	GO4ZERO project
Denmark	Aalborg	Cementir	Alkali absorption to TRL 7	ConsenCUS project (2021-2025)
Denmark	Aalborg	Cementir	Oxy-combustion	[GreenCem project, 2020]
France	Lumbres	Eqiom	Cryogenic separation	[Eqiom, 2022]
France	Montalieu-Vercieu	Vicat	Oxy-combustion	330 MW electrolyser by 2025
Germany	Göllheim	Dyckerhoff	Indirectly heated carbonate looping (IHCal) to TRL 6	ANICA project (2019-2022)
Germany	Hannover	HeidelbergCement	Enzyme-based post combustion capture to TRL 7	ACCSESS project (2021-2025)
Germany	Hannover	HeidelbergCement	Demonstration plant for indirect heating	LEILAC2 (2020-2025)
Germany	Hannover	HeidelbergCement	Chilled ammonia process to TRL 6	CEMCAP project (2015 – 2018)
Germany	Hannover	HeidelbergCement	Membrane-assisted CO_2 liquefaction to TRL 6	CEMCAP project (2015 – 2018)
Germany	Hannover	HeidelbergCement	Calcium looping (CaL) capture to TRL 6	CEMCAP project (2015 – 2018)
Germany	Höver	Holcim	Membrane in full-scale plant by 2026	[Holcim & Cool Planet, 2021].
Germany	Lägerdorf	Holcim	Feasibility to convert to oxyfuel	Westkueste100 project

Germany	Lägerdorf	Holcim	Testing of 2nd generation oxyfuel	Carbon2Business project
Germany	Mergelstetten	Schwenk	Pilot plant (0.15 Mt cement) with oxyfuel	Catch4climate consortium
Germany	Rüdersdorf	CEMEX	Design of Calcium Carbonate Looping	SCARLET project (2014-2017)
Germany	Rüdersdorf	CEMEX	Amine-Promoted Buffer Salts (APBS) in operation	[Carbon Clean & CEMEX, 2021]
Greece	Kamari	Titan	Ionic liquid to TRL 6	RECODE project (2017-2022)
Italy	Colleferro	HeidelbergCement	Design of oxyfuel kiln	ECRA research project
Italy	Vernasca	Buzzi Unicem	Calcium looping to TRL 7	CLEANKER project (2017-2021)
Poland	Górazdze	HeidelbergCement	Enzyme-based post combustion capture to TRL 7	ACCSESS project (2021-2025)
Poland	Kujawy	Holcim	Cryogenic separation	[European Commission, 2022]
Spain	Carboneras	Lafarge	Amine-Promoted Buffer Salts (APBS) in operation	[LafargeHolcim & Carbon Clean, 2021

Source: JRC based on company announcements

4.4.2 CO_2 transport and storage

While CO_2 capture matters most to the cement industry, CCUS projects require transport between a well to a sink or utilisation site to mature. Transport and storage technologies come in various forms and costs [GlobalCCSInstitute, 2021; GlobalCCSInstitute, 2022]. The ACCSESS project (2021-2025) strives to lift barriers across the whole chain and therefore assesses current and future CCS chains, such as ship-based offshore CO_2 transport in the North Sea. Further research will be conducted on technological solutions for enabling low-cost CO_2 transport [ACCSESS project, 2022].

The Greensand project foresees CO_2 liquefaction and its transport by boat to the storage site [Greensand description, 2020; Greensand description; 2021; Greensand project, 2020]. This approach is consistent with the Cryogenic Separation and membrane technology being tested at two European sites close to projects of common interest 12.8 and 12.9 (namely Holcim's Kujawy (PL) and Eqiom's Lumbres (FR), see above). The GO4ECOPLANET project will indeed liquefy the CO_2 captured at Kujawy and transport it by train and boat to the offshore storage sites [European Commission, 2022]. CO_2 emissions for Aalborg (DK) plant are foreseen to be stored in the North seabed through the Greensand project.

In addition, the EU innovation fund will make EUR 190 million available for the ANRAV project [European Commission, 2022]. This initiative is developing a full chain of CO_2 infrastructure around HeidelbergCement's plant in Devnya (BG), capturing capacity of 0.8 $MtCO_2$/year by 2028 with storage under the black sea [HeidelbergCement, 2022b].

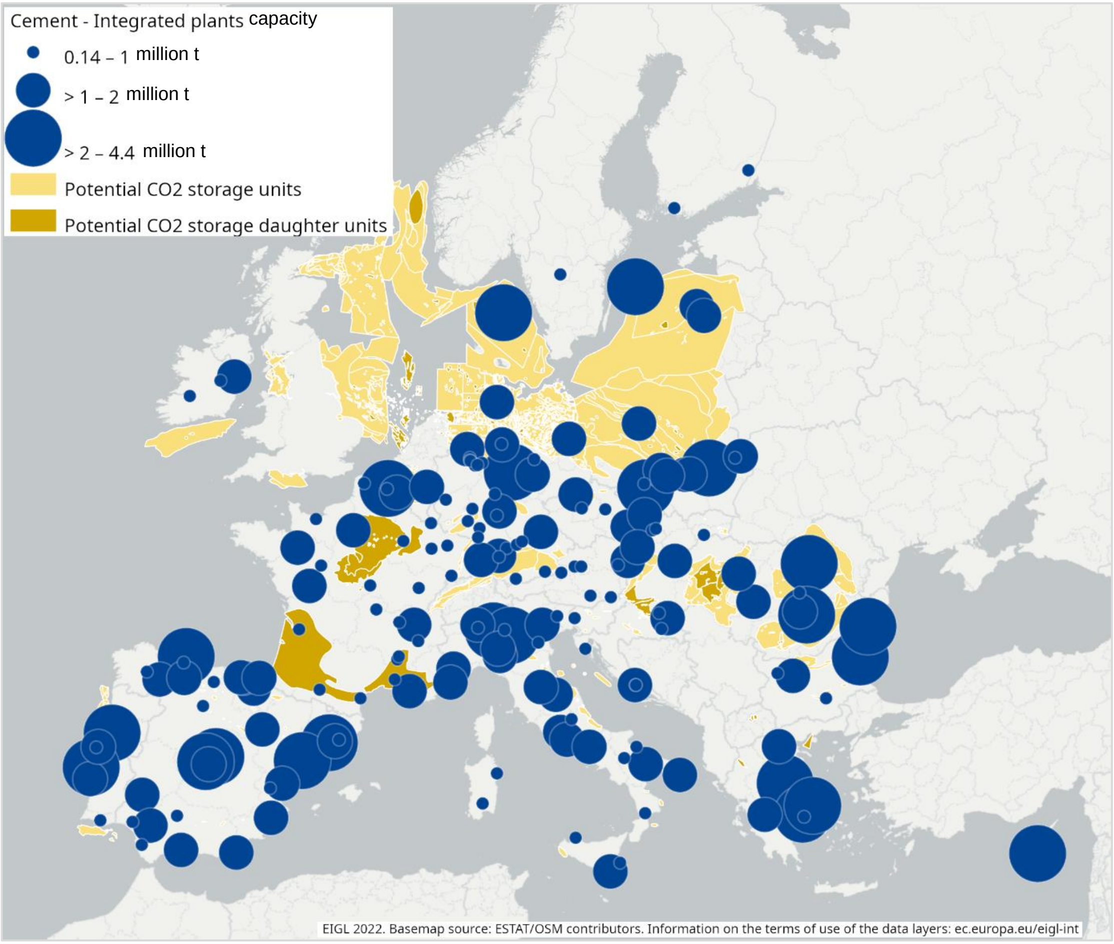
The CLEANKER project strives to model and quantify the costs of the overall CCUS chain. While several transport options (pipeline, ferry, truck, train) are considered between the participants, a pipeline is the only option modelled between well and sink. Building on the natural gas pipelines infrastructure is deemed the most economic route for CO_2 gas pipelines [CLEANKER project del. 7.1, 2019].

Regarding the location of storage sites, significant knowledge is readily available [CLEANKER project del. 7.1, 2019; ConsenSUS project del. 8.2, 2022]. The characterisation of potential CO_2 storage is an important prerequisite for the large scale deployment of CCS in Europe. In support of this, the European Commission funded the CO2StoP project (CO_2 Storage Potential in Europe), which made a first assessment of the European CO_2 storage capacity, both onshore and offshore ([14]). Mapping the EU's integrated cement plants over potential geological CO_2 storage sites in **Figure 30** shows potential for CO_2 storage in the European cement industry.

Mapping the EU's cement plants over potential geological CO2 storage sites in **Figure 31** shows that 72% of the production capacity is less than 70 km away from a suitable geological formation, and 13% of the capacity (in 24 cement plants) is located above a possible CO2 site. Only 20% of the capacity (in 33 cement plants) is located farther than 100 km from a potential CO2 storage site.

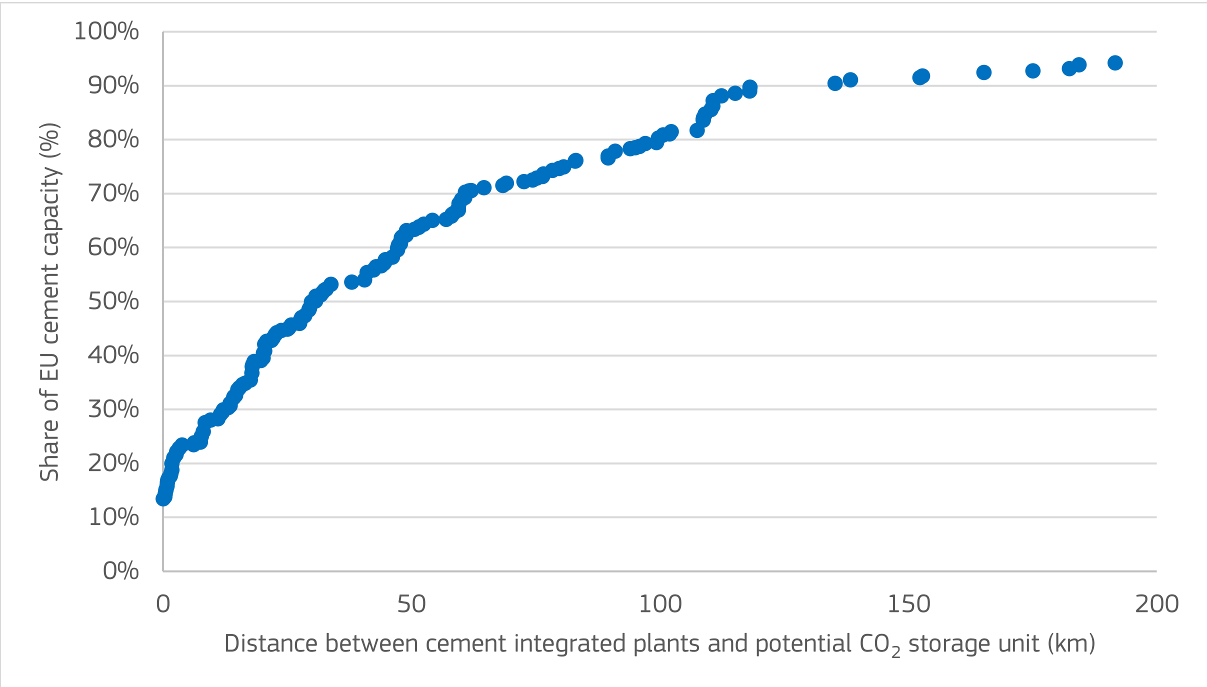
([14]) Available at: https://setis.ec.europa.eu/european-co2-storage-database_en

Figure 30 Cement integrated plants and their proximity to potential CO_2 storage sites



Source: JRC based on [GCD, 2022] and CO2StoP

Figure 31 Cement capacity vs shortest distance to potential CO_2 storage unit



Source: JRC based on [GCD, 2022] and CO2StoP

4.4.3 CO_2 utilisation

The CEMCAP project investigates post-capture CO_2 management and emerging industrial uses of CO_2 (**Figure 9**), some of which are further tested in various European sites. While cement carbonation is already covered above (see sections 4.3.1 and 4.3.4), this section focuses on the carbonation of recycled or waste materials from the construction and cement sectors. Progresses towards specific applications (greenhouse CO_2 or chemicals, including synthetic fuels) are also referred to.

Table 9 Selected key markets for CO_2 Utilisation in the EU

Product	Market size (Mt/year)	Product price (€/t)	CO_2 uptake potential (Mt/year)	Route	TRL
Aggregates	53200	20	3600	MINERALIZATION	9
Carbonated concrete	5000	25	500	MINERALIZATION	9
CO_2 food	17	80-150	17		
CO_2 greenhouse gas	5	50-80	5		9
Ethanol	87	630	166	CATALYTIC HYDROGENATION	9
Methanol	80	250	110	CATALYTIC HYDROGENATION	9

Source: CEMCAP project.

Greenhouses will be provided with CO_2 sourced at Carboneras' plant at Almería (ES). This should capture 10% of the plant CO_2 emissions from 2022, potentially reaching 100% of the plant emissions (0.7 $MtCO_2$) [Lafargeholcim, 2021b; LafargeHolcim & Carbon Clean, 2021]. Considering biomass more broadly, **algae bio-sequestration** will be demonstrated at Vicat's Montalieu-Vercieu (FR) facility, where Algosolis PhotoBioRéacteur allows for the production of 1 t dry algae/year [Vicat, 2021]. This development builds on numerous projects in the cement industry since 2009 [CimentAlgue project, 2019].

The production of various **chemicals** (formic acid, oxalic acid and glycine) is tested (TRL 6) at Titan's Kamari (HE) facility [RECODE project, 2017]. 1,800 l of formic acid is also produced daily thanks to CO_2 captured at Rohrdorfer facility [Rohrdorfer, 2022] and 2.3 kt olefin/year will ultimately by produced through the Carbon2ProductAustria project, thereby capturing almost 100% of at Lafarge's Mannersdorf (AT) emissions [C2PAT, 2022].

The production of **synthetic fuels** is also envisaged for several sites: In the frame of the Carbon2Business project [Holcim, 2022c] about 1 $MtCO_2$/year, captured at Lägerdorf (DE) plant, will be provided to the (Important Projects of Common European Interest (IPCEI) hydrogen funded) HySCALE100 installation for transformation into synthetic methanol [Holcim, 2022d]. Starting from 2025, methanol will also be produced at Vicat's Montalieu-Vercieu (FR) plant. About a quarter of France methanol demand (0.2 Mt methanol/year) could be supplied by capturing 40% of the plant's CO_2 [Vicat & Hynamics, 2021]. A feasibility study is being conducted between Buzzi Unicem and Italgas for the production of synthetic methane at Vernasca (IT) plant [Buzzi Unicem & Italgas, 2022]. 15 kt e-kerosene and e-naphtha will be produced annually, capturing 100 tCO_2/day produced by Rüdersdorf (DE) [Concrete Chemicals project, 2021]. Provided that the EUR 35 million funding is approved, Finnsementti's Lappeenranta plant may be providing CO_2 for the production of 25 kt methanol by 2026 [St1, 2022], in connection to the Decarbonate project [Decarbonate project, 2022].

Among the uses of CO_2, **carbonation** (also known as CO_2 mineralisation) is of interest for the construction sector. On one hand, it can be used for carbonation curing (see 4.3.1); on the other hand it offsets CO_2 emissions of this industry (otherwise CO_2 intensive): Re-carbonation is a naturally occurring process in which cement in concrete re-absorbs CO_2. Since carbonation reverses the calcium carbonates calcination, which is necessary in the current Portland clinker production process, one may consider that the CO_2 captured by carbonation was actually released during clinker production, even though the CO_2 molecules captured may have different origins. In theory, all CO_2 emissions from calcination can be offset by carbonation, however the two processes take place at different time: Calcination takes place in the production phase of clinker; carbonation takes place over the lifetime of the concrete and its cement. Research indicates that 23% to 30% of annual process emissions by the cement industry are captured annually by the carbonation of the cement stock in-use [IVL, 2018; Cao et al., 2020]. This process can be stimulated by increasing the surface area (thus by separating and grinding cement paste from concrete) and by increasing the CO_2 content and temperature of contact gases. Doing so increases CO_2 capture to half of CO_2 process emissions from limestone calcination. Furthermore, the carbonated material can be used as a clinker replacement in cement or as an additive in concrete [Cembureau, 2020c].

This process has only recently been referred to carbon accounting as a carbon mitigation measure [IPCC, 2021]. Assuming a conservative capture rate of 20% of emissions annually and assuming a decrease of clinker-to-cement ratio in the coming decades, global recarbonation is forecasted to lay at 242 MtCO_2 in 2050 [GCCA, 2021]. This process is however already accounted for by the industry in its quest to net-zero cement [HeidelbergCement, 2020; Holcim, 2021].

Outside the cement industry, yet within the construction sector, carbonation can be used as substitutes for natural aggregates. As opposed to calcination, this approach permanently sequesters CO_2. It relies on "alkaline" wastes, such as iron and steel slag, fly ash, lime mud, and red mud, which however may be used as alternatives to clinker. These materials can then be mobilised along two fronts for the decarbonisation of the construction sector [ISAL, 2021]. Few companies already commercialise products following this approach: (e.g., Blue Planet (15); CarbonCure (16) and Carbon8 (17)). Blue planet received financial investments from Holcim, US and Lafarge, CA [Lafarge, 2022]; Carbon8 is being commercialised at Montalieu-Vercieu, France [Vicat, 2020] and possibly in Rüdersdorf, Germany [CEMEX, 2021b]. And research is progressing: French project Fastcarb tests its technology at two locations in France [Fastcarb, 2021]; German project C^2inCO_2 has recently been launched

(15) https://www.blueplanetsystems.com/technology
(16) https://www.carboncure.com/carbon-mineralization-in-concrete/
(17) https://www.carbon8.co.uk/

[C^2inCO_2 project, 2020]; the CLEANKER project designed a pilot facility for mineralisation tests in Vernasca (IT) [CLEANKER project del. 7.5, 2019]; the RECODE project reached TRL 6 for the production of $CaCO_3$ nanoparticles to be used as concrete fillers via a packed bed reactor [RECODE project, 2017]; the Carbongreen project aims at piloting the production nanocarbons via CO_2 reduction at a cement facility [Carbongreen, 2021] and the ACCSESS project aims at improving to TRL 7 a process for carbonation of demolition fines [ACCSESS project, 2021].

Table 10 Carbon storage and utilisation projects in the EU cement industry (as of July 2022)

Country	**Plant**	**Company**	**Utilisation**
Bulgaria	Devnya	HeidelbergCement	Storage; 0.8 $MtCO_2$ by 2028. ANRAV project
Denmark	Aalborg	Cementir	Storage; 1.5 $MtCO_2$/year by 2025. Greensand project
Poland	Kujawy	Holcim	Storage; GO4ECOPLANET project
Austria	Mannersdorf	Lafarge	Utilisation; Synthetic hydrocarbons: Production of 2.3 kT polyolefin/year. [C2PAT, 2022]
Belgium	Lixhe	HeidelbergCement	Utilisation; Chemicals & building materials. RECODE project
Denmark	Aalborg	Cementir	Utilisation; synthetic fuel. GreenCem project
France	Créchy	Vicat	Utilisation; Concrete carbonation: Storing 40kgCO_2/t recycled aggregates. Fastcarb project.
France	Montalieu-Vercieu	Vicat	Utilisation; Aggregates Carbon8 CO2ntainer [Vicat, 2020] Utilisation; Methanol [Vicat & Hynamics, 2021] Utilisation; Algae through Algosolis PhotoBioReacteur [Vicat, 2021]
Germany	Lägerdorf	Holcim	Utilisation; synthetic fuel. Westkueste100 & Carbon2Business projects
Germany	Mergelstetten	Schwenk	Utilisation; Synthetic hydrocarbons [HeidelbergCement, 2020b]
Germany	Rohrdorf	Rohrdorfer	Utilisation; 1,800 l formic acid daily [Rohrdorfer, 2022]
Germany	Rüdersdorf	CEMEX	Utilisation; Aggregates through Carbon8 CO2ntainer [Cemex, 2021b] Utilisation; e-kerosene and e-naphtha: 15 kt e-kerosene and e-naphtha will be produced annually, capturing 100 tCO_2/day [Concrete Chemicals project, 2021]
Greece	Kamari	Titan	Utilisation; Chemicals & building materials. RECODE project
Italy	Vernasca	Buzzi Unicem	Utilisation; Synthetic methane [Buzzi Unicem & Italgas, 2022]
Spain	Carboneras	Lafarge	Utilisation; Agriculture. [Lafargeholcim, 2021b; LafargeHolcim & Carbon Clean, 2021]

Source: JRC based on company announcements [Cementir, 2021]

In addition to the above list, other sites have not (yet) been identified. These are the location of LafargeHolcim and Schlumberger New Energy collaboration [LafargeHolcim, 2021] and the location of Holcim and Eni collaboration, in which CO_2 will be mineralised [ENI, 2022; Holcim, 2022b].

In addition, sites in the direct vicinity of the EU provide valuable information and partners to EU projects. These are Brevik, Norway [Norcem, 2022]; Padeswood, UK [Hanson, 2021] and Ketton, UK [Hanson, 2022].

4.4.4 Costs

Techno-economic studies performed for theoretical cement plants report CO_2 abatement costs in the range from about USD 55-70/tCO_2 ([18]) avoided for oxy-fuel technologies and about USD 90-150/tCO_2 avoided for post-combustion. These costs are excluding CO_2 transport and storage and are subject to reference plant size [ECRA & WBCSD/CSI, 2017; IEAGHG, 2013].

The Zero Emissions Platform (ZEP) also reported the cost estimation for a representative new-build cement plant undertaken in the IEAGHG study [IEAGHG, 2013]. The study considered a typical production capacity of 1 Mt clinker/year, corresponding to 1.36 Mt cement/year with various carbon capture options, both post-combustion and oxy-fired. The best case for a fully oxy-fired arrangement reported, led to 84% CO_2 avoidance, with avoidance costs of EUR 40.9/tCO_2 [ZEP, 2017].

([18]) Costs are reported in 2015 USD. Costs reported in original sources are EUR 40-50 per tonne (EUR/t) avoided CO_2 for oxy-fuel and 65-110 EUR/t avoided CO_2 for post-combustion [IEAGHG, 2013]; >50 to >70 EUR/t avoided CO_2 [ECRA & WBCSD/CSI, 2017]

5 Drive towards decarbonisation

Scenarios affecting the cement industry suggest different pathways towards decarbonisation by 2050: Several technologies are expected to contribute to the decarbonisation ambition of the cement industry with their mitigation potential [Somers & Moya, 2020]. The production of low-CO_2 cement is drawing increasing attention at global level as well as in the EU. Industrial actors are coming forward with targets to achieve climate neutrality by 2050. The EU now has the opportunity to be a frontrunner in helping the industry bridge the ‘green premium’ on low-CO_2 cement by creating lead markets for green cement.

5.1 The role of R&D

The breakthrough technologies needed to decarbonise cement production are the results of decades of R&D in the sector. Before this new cement capacity is commercially deployed, the identified decarbonisation technologies still need to be moved up the TRL ladder and will require further R&D investments for pilot, demonstration and first-of-a-kind commercial plants. The different technologies identified in the previous sections have vastly different maturity levels. Some could technically be deployed today (Biomass), some still need minor process adjustments (WHR) and some are still at an early deployment stage (CCUS). Furthermore, the cost trajectory and TRL of many technologies are dependent on progress in auxiliary technologies that are not specific to the cement industry (hydrogen electrolysers, carbon capture technologies), as shown on **Figure 26**.

The European Commission has been instrumental in supporting early-stage (low TRL) R&D projects in the cement sector in the past. More broadly, the EU’s funding programme co-finance research and innovation projects in the areas of energy intensive industry and cement, including projects focussing on CO_2 emissions reduction. Funding has been made available through several programmes over the years, as can be seen in **Table 11**.

Table 11 Past/ongoing R&D funding programmes focusing on CO_2 emission reduction in cement

Funding programme	**Funding period**	**Projects**	**Budget**	**EU funding**	**TRL**
INTERREG	Since 1990	7	23.2	13.6	
LIFE	Since 1992	5	21.9	8.0	
ERA-NET	Since 2000	8	16.5	1.5	
FP7	2007-2013	31	115.9	80.6	2-7
SILC I	2011-2013	2	2.4	2.4	
RFCS	2011-2020	2	4.1	2.5	2-5
H2020	2014-2020	71	416.0	333.2	2-7
SPIRE public-private partnership	2014-2020	1	4.0	4.0	1-9
Innovation fund - large project	2020-2030	1		153	7-9
Innovation fund – small projects	2020-2030	4		TBD	7-9

Source: JRC

The 7th Framework Programme and Horizon 2020 hold the most relevant projects, funding together over 100 projects for EUR 0.53 billion. The RFCS has financed projects looking into the use of granulated blast furnace slag, an alternative to clinker. More recently, the innovation fund has provided the means to further progress on the TRL scale, funding (large and small) demonstrators and first-of-a-kind facilities.

Horizon Europe, the successor of Horizon 2020, has a budget of EUR 95.5 billion for the period 2021-2027 (30% more than H2020), of which 35% will contribute to climate objectives. Given the breadth and width of the Horizon Europe programme, only a small portion of this overall budget is likely to go to the cement sector.

The European Commission is also facilitating action on technology innovation in industry through the Implementation Working Group on energy efficiency in industry (IWG 6) of the European Strategic Energy Technology Plan (SET Plan), which brings together the European Commission, Member States, industry and research representatives to identify priority activities where funding should be targeted and agree on specific targets for technology development [IWG 6, 2021].

5.2 Global targets and pledges

There is a recent momentum shift among major industry players – globally and especially in the EU – to decarbonise cement production. Over the last years, six of the ten biggest cement producers (by 2021 cement production capacity) have announced that they aim to achieve carbon neutrality, with various intermediary 2030 targets. Together, those six cement producers accounted for 762 Mt of cement capacity production in 2021, i.e. about 19% of global cement capacity.

This picture of global ambition is tempered by the difficulty to identify targets for producers that are not active on the European market: Besides China Resources cement (Chinese cement producer), information is missing for two Chinese and two Indian based companies. Chinese CNBM and Anhui Conch are the world leaders, representing a production capacity of 914 Mt, higher than the groups duly reporting; And Indian UltraTech cement and Adani group, represent over 200 Mt of installed capacity.

Table 12 2030 and 2050 targets by five of top 10 global cement producers

Company	Headquarter location	2021 rank	Interim target	2050 target
Holcim	Switzerland	3	2030: -18% vs 2018	Net-zero across the value chain
Heidelberg Cement	Germany	4	2030: -30% vs 2020	Net-zero cement and concrete
CEMEX	Mexico	6	2030: -40% vs 1990	Net-zero company
Votorantim	Brazil	9	2030: -32% vs 1990	Carbon-neutral concrete
CRH	Ireland	10	2030: -25% vs 2020 (1)	Carbon-neutral across the value chain

(1) Targets relate to absolute emission reduction, not CO_2 emissions intensity.

Source: JRC based on company statements

In the EU, however, the picture is quite different. All the biggest EU cement producers have set carbon neutrality or close to carbon neutrality targets by 2050, underscored by the EU cement association's targets to achieve zero net emissions by then. **It is worth noting that Cembureau 2030 target implies a CO_2 emissions reduction of 30% for cement and of 40% down the value chain by 2030 compared to 1990** [Cembureau, 2020c]. This highlights the difficulty to decarbonise cement over concrete, and thus calls for scrutiny on the scope of the claims.

However, while net-zero targets or pledges are clearly an important marker of a company's ambition, they are in and of themselves non-binding and unenforceable. In the EU context, the European Climate Law [European Commission, 2020a], which sets a legally binding target of net-zero greenhouse gas emissions by 2050, indicates that it is a question of how, not if, EU cement producers will follow up on their targets. It is therefore not surprising that all major cement makers, even multinational companies such as Holcim and CEMEX, now have low-CO_2 cement projects running at several EU sites, as shown in section 4 of this report.

A leap is however required for integrating the various decarbonisation approaches into carbon-neutral cement production. **Table 13** lists the only four (of approx. 200) EU cement plants that have announced aiming at carbon neutrality. **It is worth noting that the projects at Obourg and Lumbres are targeting small cement production lines currently operating the less-efficient wet process**.

Table 13 Carbon neutrality plans at EU cement plants (as of July 2022)

Location	**Country**	**Company**	**2021 capacity (Mt)**	**Company-wide 2050 CO_2 target**
Obourg (GO4ZERO project)	Belgium	Holcim	1.7	Yes
Lumbres (K6 project)	France	Eqiom	0.7	Yes
Rüdersdorf (Carbon neutral alliance)	Germany	CEMEX	1.9	Yes
Slite [Cementa, 2021]	Sweden	Cementa HeidelbergCement	2.5	Yes

Source: JRC based on company statements

6 Conclusions

This report is a compendium of research, innovation and early signs of deployment of options for the decarbonisation of the cement industry, which are at different levels of maturity in the EU.

The EU cement sector is faced with transformational challenges if it is to reduce its CO_2 emissions on the way to a carbon-neutral future. The technologies needed to achieve the cement industry's transition are still at various stages of development, yet carbon neutral cement plants are already in the making.

The in-depth analysis of such decarbonised cement plants would provide the state-of-the-art for technological options expected to be rolled-out in the near future. Such study will also provide clues on the capacity of the sector to remain competitive while transitioning towards carbon neutrality. These initiatives build on and materialise current and ongoing decarbonisation efforts.

Energy efficiency measures, addressing thermal process inefficiencies and their emissions, **are already largely implemented**: EU cement production mostly relies on the dry process, with efficiency adds-on such as pre-heaters, pre-calciner or in few cases cogeneration or waste heat recovery options. As CCUS may however require thermal energy, the symbiosis between the cement production process and its decarbonisation through CCUS may call for attention.

The ongoing trend towards lower CO_2 intensive cement **focuses on alternative fuels** (and again emissions from the combustion for thermal processes). The current high prices of energy commodities reinforce the search for available and affordable energy carriers. Few plants already operate without fossil fuels and others are being modified towards this objective. Whether thermal energy is sourced in waste (with possibly a lower CO_2-intensity) or with biomass (deemed carbon-neutral under the ETS), switching fuel will be on a case by case basis, depending on local availability and price of alternatives, especially in the presence of competitors (incinerators or thermal power plants).

Carbon Capture, Utilisation and Storage is the most promising decarbonisation option for the cement sector: it allows for the capture of CO_2, irrespective of its origin (i.e. both from the calcination of limestone and from the combustion of fuels). However, CCUS requires the development of additional downstream processes: the industry will only be decarbonised provided that infrastructures for the transport and storage or applications for the Utilisation of captured CO_2 are available. EU funding will be instrumental in setting up such large pilot and demonstration projects.

Another approach towards decarbonising the cement industry implies **future breakthrough in chemistry**: Most of the emissions from the industry stem from the predominant position of Portland cement on the market and its emission intensive production process. Alternative production processes (including circularity) and/or alternative cement chemistries may partially solve this problem. While some alternatives do exist, their market shares remain low. Specific studies, focusing on analysing patents for possible breakthroughs; material availability; or barriers to commercialisation of such cements, would shed light on this secondary side of the industry.

The above mentioned options to decarbonise cement production carry risks. The EU and Member States have a number of demand and supply-side instruments in their policy toolbox that can be deployed to create a supportive regulatory environment, including carbon contracts for difference, green cement standards and green public procurement. The sharply rising CO_2 price of the EU ETS can provide a push towards decarbonisation and reinforce the need for a CBAM to level the global playing field, if the cement industry is facing the full CO_2 price. The Innovation Fund, funded by the EU ETS and already mobilised in the cement industry, can support the commercial demonstration of first-of-a-kind plants. At the same time, R&D support for earlier stage technologies that can be deployed closer to 2050 also needs to be maintained and strengthened to further develop additional promising breakthrough solutions for climate-neutral steel.

There is an increased policy drive towards decarbonisation of the cement industry, and the industry has responded with ambitious decarbonisation pledges. The EU can now build on this momentum and be a frontrunner in the production of CO_2-free cement. The EU cement sector can lead the way in deploying decarbonisation technologies, thereby ensuring that it stays competitive as the world transitions towards climate neutrality.

References

A.Spire. (2020). *P4Planet 2050 Roadmap*. Available at: https://www.aspire2050.eu/sites/default/files/users/user85/p4planet_07.06.2022._final.pdf

AC²OCem project Del. 4.1. (2021). *Accelerating Carbon Capture using Oxyfuel technology in Cement production*. Available at: http://ac2ocem.eu-projects.de/LinkClick.aspx?fileticket=FZoRE23FOFA%3d&tabid=1061&mid=2109

ACCSESS description. (2021). Available at: https://cordis.europa.eu/project/id/101022487

ACCSESS project. (2021). *Providing access to cost-efficient, replicable, safe and flexible CCUS*. Available at: https://www.projectaccsess.eu/

ACCSESS project. (2022). *Introducing ACCSESS: Redefining CCS*. Available at: https://www.projectaccsess.eu/2022/05/23/introducing-accsess-redefining-ccs/

Agora Energiewende and Wuppertal Institute. (2021). *Breakthrough Strategies for Climate- Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition*. www.agora-energiewende.de.

ANICA description. (2022). Advanced *indirectly heated carbonate looping process*. Available at: https://www.era-learn.eu/network-information/networks/act/act-second-call/advanced-indirectly-heated-carbonate-looping-process

ANICA project. (2022). Available at: https://act-anica.eu/

ANICA. (2022). *Application in Cement Plants*. Available at: https://act-anica.eu/application-in-cement-plants/

ARPA-E. (2020). *Co-Generation of Low-Energy, CO2-Free Hydrogen and Ordinary Portland Cement from Ca-Rich Basalts*. Available at: https://arpa-e.energy.gov/technologies/projects/co-generation-low-energy-co2-free-hydrogen-and-ordinary-portland-cement-ca

ASH-CEM (2016). *ASH-CEM: Novel Cements & Building Materials from Incineration Ashes*. Available at: https://www.sim-flanders.be/projects/ash-cem-icon/

ATEC. (2019). *References cement*. Available at: https://www.atec-ltd.com/images/Reference_List_IN_PROGRESS_01_2019.pdf

ATEC. (2022). *LafargeHolcim, Mannersdorf (AT)*. Available at: https://www.atec-ltd.com/en/references/lafargeholcim-mannersdorf-at/496.html

Ba, M., Xue, T., He, Z., Wang, H., & Liu, J. (2019). *Carbonation of magnesium oxysulfate cement and its influence on mechanical performance*. Construction and Building Materials, Volume 223, 2019, Pages 1030-1037, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2019.07.341.

BNB project. (2018). *Beton naar hoogwaardig beton*, 2014 - 2020 INTERREG V-A Belgium - The Netherlands (Vlaanderen - Nederland). Available at: https://keep.eu/projects/19326/Beton-naar-hoogwaardig-beto-EN/ & https://www.grensregio.eu/projecten/beton-naar-hoogwaardig-beton

Brinkmann, T.; Notzke, H.; Pohlmann, J.; Wolff, T.; Stecher, A.; Corner, A.; & Gorringe, S. (2022). *CO_2 separation by membrane technology: Application in the cement industry based on pilot scale research*. In: Cement International. Vol. 20 (2022) 1, 20 - 23.

Buzzi Unicem & Italgas (2022). *Buzzi Unicem and Italgas work together towards the decarbonization of cement production processes*. Available at: https://www.buzziunicem.it/web/italia/media/news/buzzi-unicem-e-italgas-insieme-verso-la-decarbonizzazione-dei-processi-produttivi-dei-cementi?languageId=en_US

BZE. (2017). *Zero Carbon Industry Plan - Rethinking Cement*. Available at: http://bze.org.au

C²inCO2 project. (2020). *C²inCO2: Calcium Carbonation for industrial use of CO2*. Available at: https://co2-utilization.net/en/projects/co2-mineralization/c2inco2/

C2PAT. (2022). *Carbon2ProductAustria - Transforming the Green Deal's aspiration into reality!* Available at: https://energieinstitut-linz.at/wp-content/uploads/2022/02/IETS-21-Circular-Carbon-2-3-Kitzweger-Haider.pdf

Cadix, A., & James, J. (2022). *Chapter 5 - Cementing additives*. Fluid Chemistry, Drilling and Completion, Oil and Gas Chemistry Management Series, 2022, Pages 187-254. Available at: https://doi.org/10.1016/B978-0-12-822721-3.00008-3

Cao, Z., Myers R. J., Lupton R. C., Duan H., Sacchi R., Zhou N., Miller T. R., Cullen J. M., Ge Q., & Liu G., (2020). *The sponge effect and carbon emission mitigation potentials of the global cement cycle*. Nature Communications, 11(1), 1–9, doi:10.1038/s41467-020-17583-w.

Carbon Clean. (2022). *What is solvent-based carbon capture?* Available at: https://www.carbonclean.com/solvents?hsLang=en

Carbon Clean & CEMEX. (2021). *CEMEX and Carbon Clean work on carbon capture project in Germany*. Available at: https://www.carbonclean.com/media-center/news/cemex-carbon-capture-project

Carbongreen project. (2021). *NanoCARBONs from GREEN house gasses of cement industry.* Available at: https://www.carbongreenproject.com/

Casale M. (2021). *CO_2 Focus Roadshow*. Available at: https://www.buzziunicem.com/documents/20143/0/CO2%20Focus%20Roadshow%20-%20Mediobanca.pdf/2ec455f0-7a6f-8168-fc83-bbc76e65c801?version=1.0

Catch4climate. (2021). *Bericht über Informationsforum Mergelstetten (vorgezogene freiwillige Bürgerbeteiligung*). Available at: https://catch4climate.com/wp-content/uploads/2022/02/Bericht_Informationsforum_Catch-for-Climate_Mergelstetten_Synopse-Version-3.pdf

Catch4climate. (2021b). Oxyfuel Verfahren. Available at: https://catch4climate.com/wp-content/uploads/2022/02/Vortrag-Oxyfuel-Verfahren.pdf

Catch4climate. (2022). *Pressemitteilung*. Available at: https://catch4climate.com/polysius-pure-oxyfuel-technology-fur-die-co2-abscheidung-in-der-zementproduktion/

CCUS projects network. (2019). *High Level Report: CCUS in Europe*. Available at: https://www.ccusnetwork.eu/sites/default/files/HLR%20_CCUS-in-Europe.pdf

CEDelft. (2021). *Waste Incineration under EU ETS*. Available at: https://cedelft.eu/wp-content/uploads/sites/2/2021/10/CE_Delft_210308_Waste_Incineration_under_the_EU_ETS_FINAL.pdf

Celitement. (2022). *When can the commissioning of an industrial production plant for Celitement be expected?*. Available at: https://celitement.de/en/faq/industrial-reference-plant/

Cembureau. (2013). *The role of cement in the 2050 low carbon economy*. Available at: https://cembureau.eu/media/cpvoin5t/cembureau_2050roadmap_lowcarboneconomy_2013-09-01.pdf

Cembureau. (2018). *Our progress on the road to 2050.* Available at: https://lowcarboneconomy.cembureau.eu/5-years-on/our-progress/

Cembureau. (2020). *Key Facts & Figures*. Available at: https://cembureau.eu/about-our-industry/key-facts-figures/

Cembureau. (2020b). *Powering the Cement Industry.* Available at: https://cembureau.eu/media/ckkpgrg1/cembureau-view-cement-sector-electricity-use-in-the-european-cement-industry.pdf

Cembureau. (2020c). *Cementing the European Green Deal, reaching carbon neutrality along the cement and concrete value chain by 2050*. Available at: https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf

Cembureau. (2022). Map of Innovation Projects. Available at: https://cembureau.eu/about-our-industry/innovation/map-of-innovation-projects/

CEMCAP project. (2018). *CEMCAP Technological achievements key conclusions*. Available at: https://www.sintef.no/globalassets/project/cemcap/presentasjoner/17-oct-2018/3_cemcap_technological_achievements_key_conclusions_k.jordal.pdf

CEMCAP project WP9. *WP9 Oxyfuel clinker cooler prototype*. Available at: https://www.sintef.no/projectweb/cemcap/research/oxyfuel-capture-retrofit-sp3/wp9-oxyfuel-clinker-cooler-prototype/

Cementa. (2021). *Sweden first in the world with carbon-neutral cement plant*. Available at: https://www.cementa.se/en/sweden-first-in-the-world-with-carbon-neutral-cement-plant

Cementir. (2021). *Cementir starts a Carbon Capture and Storage project in 2022*. Available at: https://www.cementirholding.com/en/media/whats-new/cementir-starts-carbon-capture-and-storage-project-2022

Cementirholding. (2022). *FUTURECEM® – Low carbon cement technology*. Available at: https://www.cementirholding.com/en/our-business/innovation/futurecemtm

Cementos Cruz. (2022). *Cementos Cruz presenta el proyecto reince*. Available at: https://www.cementoscruz.com/cementos-cruz-presenta-el-proyecto-reince/

CEMEX. (2021). *CEMEX successfully deploys hydrogen-based ground-breaking technology*. Available at: https://www.cemex.com/-/cemex-successfully-deploys-hydrogen-based-ground-breaking-technology

CEMEX. (2021b). *CEMEX and Carbon8 Systems partner to develop low-carbon construction products*. Available at: https://www.cemex.com/-/cemex-and-carbon8-systems-partner-to-develop-low-carbon-construction-products

CEMEX. (2022). *CEMEX and partners inaugurate the Carbon Neutral Alliance at Rüdersdorf cement plant*. Available at: https://www.cemex.com/-/cemex-and-partners-inaugurate-the-carbon-neutral-alliance-at-rudersdorf-cement-plant

CEMEX. (2022b). *CEMEX invests in breakthrough clean hydrogen technology*. Available at: https://www.cemex.com/-/cemex-invests-in-breakthrough-clean-hydrogen-technology

Cemnet. (2022). *Spain's cement sector closes plants as energy prices rocket*. Available at: https://www.cemnet.com/News/story/172384/spain-s-cement-sector-closes-plants-as-energy-prices-rocket.html

CemZero project. (2018). *A feasibility study evaluating ways to reach sustainable cement via the use of electricity*. Available at: https://www.cementa.se/sites/default/files/assets/document/65/de/final_cemzero_2018_public_version_2.0.pdf.pdf

CEWEP. (2018). *Bottom Ash Factsheet*. Available at: https://www.cewep.eu/wp-content/uploads/2017/09/FINAL-Bottom-Ash-factsheet.pdf

CEWEP. (2020). *Residual Waste Treatment Capacity Fact Sheet*. Available at: https://www.cewep.eu/wp-content/uploads/2020/12/Residual-waste-treatment-capacity-factsheet-2020.pdf

CEWEP. (2022). Personal communication with CEWEP. Figure similar to [CEWEP, 2020] based on [Eurostat data, 2020].

Chatham House. (2018). *Making Concrete Change Innovation in Low-carbon Cement and Concrete*. Available at: https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

CICECO. (2019). *From ashes to 'green' cement*. Available at: https://www.ciceco.ua.pt/?menu=255&language=eng&tabela=geral_article&id_article=643

CimentAlgue project. (2019). *«CIMENTALGUE» PROJECT Pilot & stage 1*. Available at: https://www.carbon4pur.eu/wp-content/uploads/2018/11/Session_3_05_Carbon4PUR_Lombard.pdf

Cimpor. (2010). *DECLARAÇÃO AMBIENTAL ATUALIZADA 2020 CENTRO DE PRODUÇÃO DE ALHANDRA*. Available at: https://www.cimpor.com/documents/20124/158764/DA+Alhandra_2010.pdf/ef3b719c-f5e2-06dc-3b86-b7302fbb1d72?t=1602165405876

Cimpor. (2011). *DECLARAÇÃO AMBIENTAL ATUALIZADA 2020 CENTRO DE PRODUÇÃO DE SOUSELAS*. Available at: https://www.cimpor.com/documents/20124/158764/DeclaracaoAmbientalEMAS_CPSouselas_Atualizacao_2011.pdf/802a1b48-8a61-deff-1422-584fbc940dc6?t=1602156421737

Cimpor. (2021a). *DECLARAÇÃO AMBIENTAL ATUALIZADA 2020 CENTRO DE PRODUÇÃO DE ALHANDRA*. Available at: https://www.cimpor.com/documents/20124/343251/DA_Atualizada_2020_CPA_Final_site.pdf/c6f21dcd-bef9-61a9-538c-e9f18d848c5a?t=1634228899029

Cimpor. (2021b). *DECLARAÇÃO AMBIENTAL ATUALIZADA 2020 CENTRO DE PRODUÇÃO DE SOUSELAS*. Available at:

https://www.cimpor.com/documents/20124/343251/DA_Atualizada_2020_CPS_Final_site.pdf/baa89b15-1842-3e38-e2d4-1f3a34a1b822?t=1634228932616

CLEANKER description. (2017). Available at: https://cordis.europa.eu/project/id/764816

CLEANKER project. (2017). *CLEAN clinKER production by Calcium looping process*. Available at: http://www.cleanker.eu/

CLEANKER project del. 7.1. (2019). *Definition of a methodology for the development of a techno-economic study for CO_2 transport, storage and utilization*. Available at: http://www.cleanker.eu/downloads/cleanker-public-deliverables/d71-definition-of-a-methodology-for-the-development-of-a-techno-economic-study-for-co2-transport-storage-and-utilization.html

CLEANKER project del. 7.5. (2019). *Design and full specifications of the pilot facility for mineralization tests in Vernasca*. Available at: http://www.cleanker.eu/downloads/cleanker-public-deliverables/d75-design-and-full-specifications-of-the-pilot-facility-for-mineralization-tests-in-vernasca.html

Climate Action Tracker. (2017). *Manufacturing a low-carbon society: How can we reduce emissions from cement and steel?*

Climate Strategy. (2014). *Carbon Control and Competitiveness Post 2020: The Cement Report*.

CMA & IIP. (2016). *Action Plan for Enhancing the Use of Alternate Fuels and Raw Materials in the Indian Cement Industry*.

CNBC. (2022). *These scientists bonded over toilet tech. Now they're working on carbon-free cement*. Available at: https://www.cnbc.com/2022/04/28/carbon-free-cement-breakthrough-dcvc-put-55-million-into-brimstone.html

CO2OLHEAT. (2021). *Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat*. H2020 grant agreement N° 101022831. Available at: https://co2olheat-h2020.eu/

Colacem. (2020). *Rapporto di sostenibilita 2020*. Available at: https://www.colacem.com/media/userfiles/files/Rapporto%20di%20Sostenibilit%C3%A0%20Colacem%202020.pdf

Concrete Chemicals project. (2021). *Concrete Chemicals - Pioneers in CO2nversion*. Available at: https://www.concrete-chemicals.eu/

ConsenSUS description. (2021). *CarbOn Neutral cluSters through Electricity-based iNnovations in Capture, Utilisation and Storage*. Available at: https://cordis.europa.eu/project/id/101022484

ConsenSUS project. (2021). Available at: https://consencus.eu/

ConsenSUS project del. 8.2. (2022). *ConsenCUS deliverable 8.2 - CO_2 pull market analysis.* Available at: https://consencus.eu/wp-content/uploads/2021/05/ConsenCUS_D8.2_DatabaseOfCO2UtilizationAndStorage_1.0_2205.pdf

CWGRP. (2022). *Cement ex-works prices to increase in Europe in 2Q2022 amid spiking energy costs*. Available at: https://www.cwgrp.com/cemweek-features/543646-cement-ex-works-prices-to-increase-in-europe-in-2q2022-amid-spiking-energy-costs

Decarbonate project. (2022). *Decarbonate project – Public Final Report*. Available at: https://www.decarbonate.fi/wp-content/uploads/2022/06/Decarbonate_Final_report.pdf

Dhas, S. (2021). *Decarbonisation pathways for the cement industry*.

EASAC. (2020). *Comment on the Commission consultation on the ETS*. Available at: https://easac.eu/fileadmin/PDF_s/Press_Releases/EASAC_ETS_PR_Annex.pdf

EBRD. (2016). *Low-Carbon Roadmap for the Egyptian Cement Industry -- Project "Egypt: Technology and Policy Scoping for a Low-Carbon Egyptian Cement Industry"*.

ECOFYS on behalf of EULA. (2014). *Competitive and Efficient Lime Industry - Cornerstone for a Sustainable Europe*.

ECOFYS. (2016). *Market opportunities for use of alternative fuels in cement plants across the EU - Assessment of drivers and barriers for increased fossil fuel substitution in three EU member states: Greece, Poland and Germany*.

ECOS. (2020). *Ecostandard, Breaking down barriers to lower-carbon cements – ECOS brings solutions to concrete problems*. Available at: https://ecostandard.org/breaking-down-barriers-to-lower-carbon-cements-ecos-brings-solutions-to-concrete-problems/

ECRA. (2016). *Evaluation of energy performance in cement kilns in the context of co-processing*.

ECRA. (2016b). *ECRA CCS Project Phase IV.A*. Available at: https://ecra-online.org/fileadmin/redaktion/files/pdf/ECRA_Technical_Report_CCS_Phase_IV_A.pdf

ECRA. (2018). *Cement industry launches an industrial-scale carbon capture project*. Available at: https://ecra-online.org/fileadmin/ecra/press_releases/Cement_Industry_Launches_Industrial-Scale_Carbon_Capture_Project.pdf

ECRA & WBCSD/CSI. (2017). *CSI/ECRA-Technology Papers 2017 Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead*. Available at: https://ecra-online.org/fileadmin/redaktion/files/pdf/CSI_ECRA_Technology_Papers_2017.pdf

Ember. (2022). *Daily Carbon Prices*. Available at: https://ember-climate.org/data/carbon-price-viewer/

EN 14647. (2005). *EN 14647:2005, Calcium aluminate cement - Composition, specifications and conformity criteria*.

EN 15743. (2015). *EN 15743:2010+A1:2015, Supersulfated cement - Composition, specifications and conformity criteria*.

EN 197-1. (2011). *EN 197-1:2011, Cement — Part 1: Composition, specifications and conformity criteria for common cements*.

EN 197-5. (2021). *EN 197-5:2021, Cement - Part 5: Portland-composite cement CEM II/C-M and Composite cement CEM VI*.

EN 206. (2021). *EN 206:2013+A2:2021, Concrete - Specification, performance, production and conformity*.

ENI. (2022). *CCUS, technologies playing a key role in the decarbonization process*. Available at: https://www.eni.com/en-IT/low-carbon/ccus-innovative-technologies.html

EP. (2022). *Fit for 55 in 2030: MEPs put forward demands on Emissions Trading System reform*. Available at: https://www.europarl.europa.eu/news/en/press-room/20220516IPR29663/fit-for-55-in-2030-meps-put-forward-demands-on-emissions-trading-system-reform

Eqiom. (2022). *Le projet d'EQIOM et d'Air Liquide dans le nord de la France sélectionné par le Fonds européen d'innovation*. Available at: https://www.eqiom.com/actus/le-projet-deqiom-et-dair-liquide-dans-le-nord-de-la-france-selectionne-par-le-fonds-europeen

Espacenet. (2022). *New formulation for a low-carbon construction binder comprising, method of production, and construction materials*. https://worldwide.espacenet.com/patent/search?q=pn%3DWO2020141285A1

ETC. (2018). *Mission Possible, Reaching Net-Zero carbon emissions from harder-to-abate sectors by mid-century*.

ETH. (2018). *A sustainable future for the European Cement and Concrete industry - Technology assessment for full decarbonisation of the industry by 2050*.

European Commission. (2013). *COM(2013) 163.* C*ommission Implementing Decision of 26 March 2013 establishing the best available techniques (BAT) conclusions under Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions for the production of cement, lime and magnesium oxide.*

European Commission. (2013b). *Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide*. In Publications Office of the European Union. https://doi.org/10.2788/12850.

European Commission. (2018). *Competitiveness of the European cement and lime sectors: final report.* Available at: https://data.europa.eu/doi/10.2873/300170

European Commission. (2020a). *COM(2020) 80 final*.

European Commission. (2020b). *COM(2020) 102 final*.

European Commission. (2020c). *SWD(2020) 176 final*.

European Commission. (2020d). *COM(2020) 628 final*.

European Commission. (2021). *PCI 12.9. Poland – EU CCS Interconnector (emitters from the industrial cluster in the area around Gdansk, Poland with storage where available in the North Sea country territories) - Cross-border carbon dioxide network*. Available at: https://ec.europa.eu/energy/maps/pci_fiches/PciFiche_12.9.pdf

European Commission. (2021a). *COM(2021) 350 final.*

European Commission. (2021b). *COM(2021) 551 final*.

European Commission. (2021c). *COM(2021) 564 final*.

European Commission. (2021d). *SWD(2021) 277 final*.

European Commission. (2021e). *COM(2021) 800 final.*

European Commission. (2021f). Regulation (EU) 2021/1119: European Climate Law.

European Commission. (2022). *Innovation fund second call for large-scale projects - List of proposals pre-selected for a grant*. Available at: https://ec.europa.eu/clima/system/files/2022-07/LSC2_List_of_pre-selected_projects_6.pdf

European Commission. (2022a). *ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries*.

European Commission. (2022b). COM(2022) 230 final.

European Commission. (2022c). SWD(2022) 230 final.

European Commission. (2022d). *State Aid: Commission approves up to EUR 5.2 billion of public support by thirteen Member States for the second Important Project of Common European Interest in the hydrogen value chain*. Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5676

European Commission. (2022e). *What is strategic foresight?* Available at: https://ec.europa.eu/info/strategy/strategic-planning/strategic-foresight_en

European Commission. (2022f). *Sustainable Industry Low Carbon (SILC).* Available at: https://single-market-economy.ec.europa.eu/industry/sustainability/climate-neutral-economy/sustainable-industry-low-carbon-silc_en

European Environmental Agency. (2022). *EU Emissions Trading System (ETS) data viewer*. Activity code 29 Production of cement clinker. Available at https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1.

European Environmental Agency. (2022b). *Greenhouse gas emission intensity of electricity generation in Europe*. Available at: https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1

European Parliament and Council of the EU. (2021). *Regulation (EU) 2021/1119.*

Eurostat. (2019). *Renewables annual questionnaire 2017-2021 and historical revisions*. Available at: https://ec.europa.eu/eurostat/documents/38154/10015688/Ren-Instructions-2018.pdf/bc81e198-d1fc-4799-bb35-f5f4f252e19b

Eurostat. (2020). *Municipal waste by waste management operations* [env_wasmun]

Eurostat. (2021). *Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) [sbs_na_ind_r2].*

Eurostat. (2022). *Sold production, exports and imports* [DS-066341].

Exergy. (2020). *Waste Heat Recovery Cementi Rossi*. Available at: https://www.exergy-orc.com/references/case-studies/heat-recovery-cases/waste-heat-recovery-cementirossi

Fastcarb. (2021). *Etat d'avancement du Projet National FastCarb*. Available at: https://fastcarb.fr/2021/02/01/etat-davancement-du-projet-national-fastcarb/

Fediuk. R., Mochalov, A., & Timokhin, R. (2018). *Review of methods for activation of binder and concrete mixes*. AIMS Materials Science 2018, Volume 5, Issue 5: 916-931. doi: 10.3934/matersci.2018.5.916

FLSmidth. (2021). *FLSmidth delivers MissionZero flagship solution to Cimpor Cement.* Available at: https://www.flsmidth.com/en-gb/company/news/news-and-events/2021/chlorine-bypass-solution-cimpor-cement

FLSmidth. (2021b). *FLSmidth cuts up to 16% CO2 with Europe's first full-scale clay calcination installation*. Available at: https://www.flsmidth.com/en-gb/company/news/company-announcements/2021/flsmidthcutsupto16co2witheuropesfirstfullscaleclaycalcinationins

FONA. (2022). *Carbon2Chem*. Available at: https://www.fona.de/en/measures/funding-measures/carbon2chem-project.php

Fossil Free Sweden. (2020). *Roadmap for fossil free competitiveness Summaries 2018–2020*.

Futures Platform. (2022a). *Carbon-Neutral Cement*. Available at: https://www.futuresplatform.com/

Futures Platform. (2022b). *Doubling the Number of Buildings*. Available at: https://www.futuresplatform.com/

Futures Platform. (2022c). *Concrete Out of Waste*. Available at: https://www.futuresplatform.com/

Futures Platform. (2022d). *Sand Suitable for Building*. Available at: https://www.futuresplatform.com/

Futures Platform. (2022e). *Self-Healing Bio-Concrete*. Available at: https://www.futuresplatform.com/

Futures Platform. (2022f). *Self-Maintaining Buildings*. Available at: https://www.futuresplatform.com/

Gartner, E., & Sui, T. (2018). *Alternative cement clinkers, Cement and Concrete*. Research 114 (2018) 27–39.

GCCA. (2019). *Getting the Numbers Right Project, Emissions Report 2019*.

GCCA. (2020). *The Cement CO_2 and Energy Protocol, Version 3. CO_2 and Energy Accounting and Reporting Standard for the Cement Industry. Internet Manual for Printout*.

GCCA. (2021). *The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete*.

GCCA. (2022). *Limestone filler*. Available at: https://gccassociation.org/cement-and-concrete-innovation/clinker-substitutes/limestone-filler/

GCD. (2022). *Global Cement Directory, GlobalCement, 2022*.

Global Carbon Project. (2022). *Carbon budget and trends 2021*. Available at: www.globalcarbonproject.org/carbonbudget

Global Cement Magazine. (2022). *Global Cement Magazine. July-August 2022*.

Global Cement. (2021). *Global Cement Alternative Fuels Special Issue*. Available at: https://www.cemfuels.com/reports

Global Cement. (2022). *Update on electric cement kilns.* Available at: https://www.globalcement.com/news/item/14256-update-on-electric-cement-kilns?utm_source=newsletter&utm_medium=email&utm_content=567926&utm_campaign=gcw561

Global Cement. (2022a). *FYM-HeidelbergCement suspends clinker production at Málaga cement plant*. Available at: https://www.globalcement.com/news/item/13847-fym-heidelbergcement-suspends-clinker-production-at-malaga-cement-plant

Global Cement. (2022b). *Adani Group and other mega-deals in the cement industry*. Available at: https://www.globalcement.com/news/itemlist/tag/Holcim%20Brasil

Global Efficiency Intelligence. (2021). *Deep decarbonization roadmap for the cement and concrete industries in California*.

GlobalCCSInstitute. (2021). *Technology readiness and costs of CCS*. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf

GlobalCCSInstitute. (2022). *State of the art: CCS technologies 2022*. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2022/05/State-of-the-Art-CCS-Technologies-2022.pdf

GlobBULK. (2018). *Cement consumption vs GDP per capita: A review*. Available at: http://globbulk.com/media/news/documentos/cement-consumption-gdp-per-capita.pdf

Górażdże. (2021). *Grupa Górażdże podpisała z BayWa r.e. przełomowy kontrakt na zakup energii z największej farmy fotowoltaicznej w Polsce*. Available at: https://www.gorazdze.pl/pl/grupa-gorazdze-podpisala-z-baywa-re-przelomowy-kontrakt-na-zakup-energii-z-najwiekszej-farmy-fotowoltaicznej-w-polsce

Grassano, N., Hernandez Guevara, H., Fako, P., Tübke, A., Amoroso, S., Georgakaki, A., Napolitano, L., Pasimeni, F., Rentocchini, F., Compaño, R., Fatica, S., & Panzica, R. (2022). *The 2021 EU Industrial R&D Investment Scoreboard, In Publications Office of the European Union*. https://doi.org/10.2760/559391.

GHG Protocol. (2022). *Greenhouse Gas Protocol Calculation Tools - Frequently Asked Questions*. Available at: https://ghgprotocol.org/calculationg-tools-faq

GreenCem project. (2020). *Pre-study investigating the possibilities for carbon capture in the Aalborg area*. Available at: https://greencem.dk/ and https://eudp.dk/en/node/15993

Greensand description. (2020). *Project Greensand Fase 1*. Available at: https://www.eudp.dk/en/node/16145

Greensand description. (2021). *Project Greensand Fase 2.* Available at: https://www.eudp.dk/en/node/16466

Greensand project. (2020). Available at: https://www.projectgreensand.com/en

Grimekis, D. Magiri Skouloudi, D., Braimakis, K., Avagianos, I., Doukelis, A., & Karellas, S. (2019). *Process modelling of heat utilisation options (D7.1).* Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c659a7d6&appId=PPGMS

Hanson. (2021). *Hanson one step closer to CCS as HyNet North West received government backing*. Available at: https://www.hanson.co.uk/en/news-and-events/hynet-north-west-received-government-backing

Hanson. (2022). *New CCS project trial at Ketton cement works in race to net zero*. Available at: https://www.hanson.co.uk/en/news-and-events/carbon-capture-trial-at-ketton-cement-works

Hasanbeigi, A., & Springer, C. (2019). *Deep Decarbonization Roadmap for the Cement and Concrete Industries in California*. Global Efficiency Intelligence. San Francisco, CA.

Hasanbeigi, A., Nilsson, A., Mete, G., Fontenit, G., & Shi. D. (2021). *Fostering industry transition through green public procurement: A "How to" guide for the cement & steel sectors*. Available at: https://www.industrytransition.org/content/uploads/2021/08/1-fostering-industry-transition-through-green-public-procurement.pdf

Heatleap project. (2014) Available at: https://heatleap-project.eu/heatleap-project/

HeidelbergCement. (2020). *Leading the way to carbon neutrality*.

HeidelbergCement. (2020b). *Pilot project of four cement manufacturers plans to use captured CO2 as a raw material for the production of synthetic fuels*. Available at: https://www.heidelbergcement.com/en/pr-18-11-2020

HeidelbergCement. (2021). *Next industrial scale-up of a CO_2 capture technology: LEILAC2 pilot project will be located at HeidelbergCement's Hanover cement plant*. Available at: https://www.heidelbergcement.com/en/pr-01-02-2021

HeidelbergCement. (2022). *HeidelbergCement receives German Innovation Award for Climate and Environment (IKU)*. Available at: https://www.heidelbergcement.com/en/pr-16-05-2022

HeidelbergCement. (2022b). *Pioneering CCUS in Bulgaria: HeidelbergCement's ANRAV project selected by EU Innovation Fund*. Available at: https://www.heidelbergcement.com/en/pr-12-07-2022

Heliogen. (2019). *Decarbonizing Industry with HelioHeat™.* Available at: https://heliogen.com/wp-content/uploads/2019/11/heliogen_helioheat_doc_w.pdf

HLG EII. (2019). *Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050.*

Hodges, R., & Woods, D. (2020) *Support to Sino-German Cooperation on NDC Implementation: Sectoral Best Practice*. Available at: https://climatecooperation.cn/wp-content/uploads/2021/01/Ricardo-Industrial-decarbonisation_cement_FINAL.pdf

Hoffmann Green Cement. (2022). *Construction de notre unité de production H2*. Available at: https://www.ciments-hoffmann.fr/process-industriel/unite-de-production-h2/

Hoffmann Green Cement. (2022b). *Incarner le changement de paradigme dans le secteur de la construction*. Available at: https://www.ciments-hoffmann.fr/process-industriel/unite-de-production-h2/https://www.ciments-hoffmann.fr/hoffmann-green/mission/

Holcim & Cool Planet. (2021). *Holcim und Cool Planet Technologies entwickeln eine Carbon Capture Anlage in Deutschland*. Available at: https://www.holcim.de/de/holcim-und-cool-planet-technologies-entwickeln-eine-carbon-capture-anlage-deutschland

Holcim. (2020). *Paving the way toward net zero emissions: decarbonated alternative raw materials*. Available at: https://www.holcim.com/who-we-are/our-stories/net-zero-emissions-decarbonated-alternative-raw-materials

Holcim. (2021). *Holcim net zero journey*.

Holcim. (2021b). *Présentation du projet GO4ZERO Réunion d'Information Préalable - 15 Septembre 2021*. Available at: https://www.holcim.be/sites/belgium/files/documents/presentation_rip_15_09_2021.pdf

Holcim. (2022). *GO4ZERO – Nouveau four (Obourg) – L'étude des incidences environnementales démontre la haute valeur ajoutée sur le plan environnemental et la pertinence des choix technologiques opérés par Holcim*. Available at: https://www.holcim.be/fr/go4zero-nouveau-four-obourg-etude-des-incidences-environnementales-demontre-haute-valeur-ajoutee-environnemental-pertinence-des-choix-technologiques-operes-par-holcim

Holcim. (2022a). *GO4ZERO update.* Available at: https://www.holcim.be/fr/go4zero-update

Holcim. (2022b). *Holcim and Eni explore breakthrough carbon capture storage and utilization technology*. Available at: https://www.holcim.com/media/media-releases/holcim-eni-explore-breakthrough-carbon-capture

Holcim. (2022c). *Holcim selected for 2 EU Innovation Fund grants for Clean Tech projects decarbonizing Europe*. Available at: https://www.holcim.com/media/media-releases/eu-innovation-fund

Holcim. (2022d). *Holcim net zero journey*. Climate report 2022

ICAP. (2021). *EU Emissions Trading System (EU ETS)*.

IEA & WBCSD. (2009). *Cement Technology Roadmap 2009 Carbon emissions reductions up to 2050*.

IEA & WBCSD/CSI. (2018). *Technology Roadmap Low-Carbon Transition in the Cement Industry.*

IEA. (2020). *Energy Technology Perspectives 2020*, September 2020. Available at: https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf

IEA. (2021). *Cement*. IEA, Paris. Available at: https://www.iea.org/reports/cement

IEA. (2021b). *An Energy Sector Roadmap to Carbon Neutrality in China*. CC BY-NC 3.0

IEAGHG. (2013). *Deployment of CCS in the Cement Industry*. Available at: www.ieaghg.org/docs/General_Docs/Reports/2013-19.pdf

IFC. (2014). *Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis*.

IFC. (2017). *Increasing the Use of Alternative Fuels at Cement Plants*.

IFC. (2018). *Improving thermal and electric energy efficiency at cement plants: international best practice.*

IFC. (2020). *The Impact of COVID-19 on the Cement Industry.*

IIPNetwork. (2014). *Enhancing the Use of Alternate Fuels and Raw Materials. (co-processing). in cement manufacture: white paper on selected topics.*

Imperial College London Consultants. (2021). *Sustainable biomass availability in the EU, to 2050*. Available at: https://www.fuelseurope.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf

INDAVER project. (2022). Twee projecten geselecteerd na open oproep om circulaire economie in Antwerps havengebied te stimuleren. Available at: https://www.indaver.com/be-nl/nieuws-media/nieuws-detail/twee-projecten-geselecteerd-na-open-oproep-om-circulaire-economie-in-antwerps-havengebied-te-stimule/

IPCC. (2021). *Chapter 5 - Global Carbon and other Biogeochemical Cycles and Feedbacks*. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter05.pdf

Irish Cement. (2017). *Irish Cement Platin – Investing in our future*. Available at: https://www.irishcement.ie/wp-content/uploads/2017/02/Irish-Cement-Platin-Information-Booklet-2017.pdf

ISAL. (2021). *Decarbonizing Concrete - Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China.*

IVL. (2018). *CO_2 uptake in cement-containing products Background and calculation models for IPCC implementation*. Available at: https://www.ivl.se/download/18.694ca0617a1de98f4729cf/1628413707637/FULLTEXT01.pdf

IWG 6. (2021). SET Plan Action 6 on Energy Efficiency in Industry Implementation Plan. https://setis.ec.europa.eu/system/files/2021-12/SET Plan Action6 on EE in industry-Implementation Plan-Rev2021-final-endorsed.pdf

JRC. (2022). *Interlinkages for a megatrend on accelerating technological change and hyperconnectivity*. 2022, doi:10.2760/555338, JRC126570. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC126570

K4 project. (2022). *K4 - Carbon dioxide reduction through low-lime clinker and carbonation hardening in concrete production*. Available at: https://www.fona.de/en/measures/funding-measures/KlimPro/K4.php

Khan, M. M. H., Havukainen, J., & Horttanainen, M. (2021). *Impact of utilizing solid recovered fuel on the global warming potential of cement production and waste management system: A life cycle assessment approach*. Waste Management & Research, 39(4), 561–572. https://doi.org/10.1177/0734242X20978277

Kleib, J., Aouad, G., Abriak, N.-E., & Benzerzour, M. (2021). *Production of Portland cement clinker from French Municipal Solid Waste Incineration Bottom Ash*. Case Studies in Construction Materials, Volume 15, 2021, e00629, ISSN 2214-5095, https://doi.org/10.1016/j.cscm.2021.e00629

Kleib, J., Aouad, G., Benzerzour, M., Zakhour, M., & Abriak, N.-E. (2021). *Effect of calcium sulfoaluminate cements composition on their durability*. Construction and Building Materials, Volume 307, 2021, 124952, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2021.124952

Küttner. (2022). *Rohrdorfer Zement*. Available at: https://www.kuettner.com/en/references/rohrdorfer-zement

Lafarge. (2022). *Holcim North America to Scale up Mineralization Technology Leading Industry Transition to Net Zero*. Available at: https://www.lafarge.ca/en/holcim-north-america-scale-mineralization-technology-leading-industry-transition-net-zero

LafargeHolcim & Carbon Clean. (2021). *LafargeHolcim and Carbon Clean to develop large scale CCUS plant*. Available at: https://www.carbonclean.com/media-center/news/lafargeholcim-and-carbon-clean-to-develop-large-scale-ccus-plant

LafargeHolcim. (2021). *LafargeHolcim and Schlumberger New Energy explore Carbon Capture and Storage Solutions*. Available at: https://www.holcim.com/media/media-releases/lafargeholcim-and-schlumberger-new-energy-explore-carbon-capture-and-storage-solutions

Lafargeholcim. (2021b). *Nace ECCO2, la joint-venture para el desarrollo de una planta de captura de CO_2 para uso agrícola en la fábrica de LafargeHolcim en Carboneras*. Available at: https://www.lafargeholcim.es/nace-ecco2-joint-venture-planta-captura-co2-para-uso-agricola-almeria-carboneras

Lechtenböhmer S, Nilsson L.J:, Åhman M., & Schneider C. (2016). *Decarbonising the energy intensive basic materials industry through electrification – implications for future EU electricity demand*. Energy (2016), Volume 115, Part 3, 15 November 2016, Pages 1623–1631, doi: 10.1016/j.energy.2016.07.110

Lecomte, T., Ferrería de la Fuente, J. F., Neuwahl, F., Canova, M., Pinasseau, A., Jankov, I., Brinkmann, T., Roudier, S., & Delgado Sancho, L. (2017). *Best Available Techniques (BAT) Reference Document for Large Combustion Plants.* EUR 28836 EN; doi:10.2760/949

LEILAC description. (2016). *Low Emissions Intensity Lime and Cement*. Available at: https://cordis.europa.eu/project/id/654465

LEILAC project. (2016). *Low Emissions Intensity Lime & Cement*. Available at: https://www.project-leilac.eu/

LEILAC project. (2021) *Roadmap 2050*. Available at: https://www.project-leilac.eu/leilac-roadmap-to-2050

LEILAC2 description. (2020). *Low Emissions Intensity Lime and Cement 2: Demonstration scale*. Available at: https://cordis.europa.eu/project/id/884170

Materrup. (2022). Available at: https://en.materrup.com/

McCarten, M., Bayaraa, M., Caldecott, B., Christiaen, C., Foster, P., Hickey, C., Kampmann, D., Layman, C., Rossi, C., Scott, K., Tang, K., Tkachenko, N., and Yoken, D. (2021). *Global Database of Cement Production Assets. Spatial Finance Initiative*. Available at: https://www.cgfi.ac.uk/spatial-finance-initiative/geoasset-project/geoasset-databases/

Mistra Carbon Exit. (2020). Technical roadmap - cement industry.

Möller, H. (2021). *Celitement - A novel cement based on hydraulic calcium hydrosilicates (hCHS)*. Available at: https://celitement.de/wp-content/uploads/2021/10/2021_10_28_Description_Celitement_MOE.pdf

Moya Rivera J., & Boulamanti A. (2016). *Production costs from energy intensive industries in the EU and third countries. In Publications Office of the European Union*. http://dx.doi.org/10.2790/79502.

MPA Cement. (2013). *The UK cement industry aims to reduce greenhouse gases by 81% by 2050*.

MPA, Cinar Ltd & VDZ GmbH. (2019). *Options for switching UK cement production sites to near zero CO_2 emission fuel: Technical and financial feasibility*. Available at: https://www.vdz-online.de/fileadmin/wissensportal/forschungsprojekte/Phase_2_-_MPA_-_Cement_Production_Fuel_Switching.pdf

NewClimate. (2020). *Decarbonisation pathways for the EU cement sector - Technology routes and potential ways forward.*

NGHV project. (2022). *Nazaré Green Hydrogen Valley*. Available at: https://www.nghv.pt/

Noë, H. (2021). *LafargeHolcim & Solidia*. Available at: https://betonhuis.nl/system/files/2021-11/solidia-23.11.2021-v3.pdf

Norcem. (2022). *Carbon Capture and Storage (CCS)*. Available at: https://www.norcem.no/en/CCS

Novak, T. (2022). *The role of ball mill grinding systems in the production of low carbon cement*. Live Webinar: Technologies for the production of low-carbon cement – 06th July 2022.

ONESTONE CONSULTING LTD. (2021). Latest trends in clay activation. Available at: https://www.zkg.de/en/artikel/zkg_Latest_trends_in_clay_activation_3683572.html

Opterra. (2022). *Statkraft liefert seit Anfang April weitere 300 GWh Grünstrom an Zementhersteller OPTERRA*. Available at: https://www.opterra-crh.com/presse/pressemeldungen/detail/pressrelease/statkraft-liefert-seit-anfang-april-weitere-300-gwh-gruenstrom-an-zementhersteller-opterra/

Orcan Energy. (2021a). *Wittekind cement plant intends to significantly reduce its CO_2 emissions thanks to waste heat solutions from Orcan Energy*. Available at: https://www.orcan-energy.com/en/details/wittekind-cement-plant-intends-to-significantly-reduce-its-co2-emissions-thanks-to-waste-heat-solutions-from-orcan-energy.html

Orcan Energy. (2021b). *Orcan Energy achieves major coup in the cement market*. Available at: https://www.orcan-energy.com/en/details/orcan-energy-achieves-major-coup-in-the-cement-market.html

Ormat, (2022). *Global projects*. Available at: https://www.ormat.com/en/projects/all/main/

Ottelé, M. (2021). *Positief toekomstbeeld dankzij nieuwe recycling methoden beton*. Cement: vakblad voor de betonwereld, 2022, 3, 26-34.

Pal, S.C., Mukherjee, A., & Pathak, S.R. (2003). *Investigation of hydraulic activity of ground granulated blast furnace slag in concrete*. Cement and Concrete Research, Volume 33, Issue 9, 2003, Pages 1481-1486, ISSN 0008-8846, https://doi.org/10.1016/S0008-8846(03)00062-0.

PlasticEurope. (2019). *The circular economy for plastics – A European overview*. Available at: https://plasticseurope.org/wp-content/uploads/2021/10/20191206-Circular-Economy-Study.pdf

Plaza, M. G., Martínez, S., & Rubiera, F. *CO_2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations*. Energies 2020, 13, 5692. https://doi.org/10.3390/en13215692

Prognos & CE Delft. (2022). *CO_2 reduction potential in European waste management*. Available at: https://cedelft.eu/publications/co2-reduction-potential-in-european-waste-management/

Prognos. (2018). *CEWEP Calculation Tool for potential impacts on waste amounts for thermal treatment*. Available at: https://www.cewep.eu/wp-content/uploads/2019/05/Peer-Review_waste-treatment-need-in-2035.pdf

RECEMENT project. (2018). *RE-generating (raw) materials and end-of-life products for re-use in CEMENT/Concrete*. ERA-MIN-2018_77. Available at: https://www.era-learn.eu/network-information/networks/era-min-2/era-min-joint-call-2018/re-generating-raw-materials-and-end-of-life-products-for-re-use-in-cement-concrete

RECODE description. (2017). *Recycling carbon dioxide in the cement industry to produce added-value additives: a step towards a CO_2 circular economy*. Available at: https://cordis.europa.eu/project/id/768583

RECODE project. (2017). *Abstract*. Available at: https://recodeh2020.eu/project

Rohrdorfer. (2022). *Rohrdorfer baut als erstes zementwerk in deutschland co2 abscheideanlage*. Available at: https://www.rohrdorfer.eu/rohrdorfer-baut-als-erstes-zementwerk-in-deutschland-co2-abscheideanlage/

Rootzén, J., & Johnsson, F. (2017). *Managing the costs of CO_2 abatement in the cement industry*. Climate Policy, 17:6, 781-800. http://dx.doi.org/10.1080/14693062.2016.1191007.

Rootzén. J. (2015). *Pathways to deep decarbonisation of carbon-intensive industry in the European Union - Techno-economic assessments of key technologies and measures*.

Sahu, S., & Meininger, R. C. (2019). *Performance of CO2-reducing cement based on calcium silicates*. 15th International Congress on the Chemistry of Cement Prague, Czech Republic, September 16–20, 2019. Available at: https://downloads.ctfassets.net/jv4d7wct8mc0/3tXwtJYRhIgDVpqljszFWH/d0f6dc5364a37a326412bfde32d270d5/2019_ICCC_-_Performance_of_CO2-Reducing_Cement_Based_on_Calcium_Silicates_copy.pdf

SaltX Technology. (2022). *Breakthrough in production of “green cement” – results verified by industry experts*. Available at: https://investor.saltxtechnology.com/breakthrough-in-production-of-green-cement-results-verified-by-industry-experts/

Sandalow, D., Friedmann, J., Aines, R., McCormick, C., McCoy, S., & Stolaroff J,. (2019). *ICEF Industrial Heat Decarbonization Roadmap*. Bonn, Germany: ICEF. Available at: https://www.icef.go.jp/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf

Santarossa, S. (2022). *Shrinking energy bills with ORC technology*. In World Cement magazine, July 2022.

Sartor, O., & Bataille, C. (2019). *Decarbonising Basic Materials in Europe: How Carbon Contracts-for-Difference Could Help Bring Breakthrough Technologies to Market*.

SCARLET description. (2016). *Scale-up of Calcium Carbonate Looping Technology for Efficient CO_2 Capture from Power and Industrial Plants*. Available at: https://cordis.europa.eu/project/id/608578

SCARLET project. (2016). Available at: http://www.project-scarlet.eu/

SCARLET project del. 8.8. (2016). *Deliverable D8.8 Technology Implementation Plan (TIP) – Update 2 Reporting Period P3 – month 25 to month 30*. Available at: http://www.project-scarlet.eu/wordpress/wp-content/uploads/2016/12/SCARLET_Deliverable-8.8_Technology-Implementation-Plan-TIP-Update-2.pdf

Schenckprocess. (2022). *Alternative Fuel Feeding Line*. Available at: https://www.schenckprocess.cz/cizkovice-cement-plant/

SECIL. (2020). *Clean Cement Line.* Available at: https://www.secil-group.com/en/inovacao/clean-cement-line

Singh, N.B., Kumar, M., & Rai, S. (2020) *Geopolymer cement and concrete: Properties*. Materials Today: Proceedings, Volume 29, Part 3, 2020, Pages 743-748, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2020.04.513.

SITRA. (2018). *The Circular Economy a Powerful Force for Climate Mitigation - Transformative innovation for prosperous and low-carbon industry*

SNIC. (2019). *Cement Technology Roadmap - Carbon Emissions Reduction Potential in the Brazilian Cement Industry by 2050*.

Solidiatech. *Patents, awards and investors*. Available at: https://www.solidiatech.com/accomplishments.html

SolCement project. (2021). Available at: http://www.solcement.certh.gr/E79F3162.en.aspx

SOLPart description. (2016). *High Temperature Solar-Heated Reactors for Industrial Production of Reactive Particulates*. Available at: https://cordis.europa.eu/project/id/654663

SOLPart project. (2016). *High temperature Solar-Heated Reactors for Industrials Production of Reactive Particulates*. Available at: https://www.solpart-project.eu/

Somers, J. & Moya, J. (2020). *Deep decarbonisation of industry: The cement sector*, JRC120570. Available at: https://setis.ec.europa.eu/deep-decarbonisation-industry-cement-sector_en

Somers, J. (2022). *Technologies to decarbonise the EU steel industry*, In Publications Office of the European Union. https://doi.org/10.2760/069150.

STADLER. (2021). *STADLER renovates the CITR waste management facility managed by FCC Medio Ambiente in Las Marinas, El Campello (Alicante) in Spain*. Available at: https://stadler-engineering.com/company/news/detail/stadler-renovates-the-citr-waste-management-facility-managed-by-fcc-medio-ambiente-in-las-marinas-el-campello-alicante-in-spain

Statista. (2022a). *Cement prices in the United States from 2010 to 2021*. Available at: https://www.statista.com/statistics/219339/us-prices-of-cement/

St1. (2022). *St1 is planning a synthetic methanol pilot plant in Lappeenranta, Finland*. Available at: https://www.st1.com/st1-is-planning-a-synthetic-methanol-pilot-plant-in-lappeenranta-finland

Stede, J., Pauliuk, S., Hardadi, G., & Neuhoff, K. (2021). *Carbon pricing of basic materials: Incentives and risks for the value chain and consumers*. DIWDiscuss.

Stinnessen, I,. Buhr, A,. Kockegey-Lorenz, R., & Racher, R.,. (n.d.) *High purity Calcium Aluminate cements, production and properties*. Available at: https://almatis-umbraco.azurewebsites.net/media/3985/high_purity_calcium-aluminate-cements_production_and_properties.pdf

Strunge, T., Renforth, P., & Van der Spek, M. (2022). *Towards a business case for CO_2 mineralisation in the cement industry*. Commun Earth Environ 3, 59 (2022). https://doi.org/10.1038/s43247-022-00390-0

Synhelion. (2022). *CEMEX looks to use the sun to decarbonize cement*. Available at: https://synhelion.com/news/cemex-looks-to-use-the-sun-to-decarbonize-cement

Tartière, T., & Astolfi, M. (2017). *A World Overview of the Organic Rankine Cycle Market*. Energy Procedia, Volume 129, September 2017, Pages 2-9. https://doi.org/10.1016/j.egypro.2017.09.159

TASIO project. (2014). *Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries*. Available at: https://cordis.europa.eu/project/id/637189

Taylor, H. F. W. (2007). *Cement Chemistry*. Thomas Telford Publishing, London, UK, 2nd edn, 1997. ISBN

The Graphene Council. (2021). *Graphene in Cement & Concrete Applications*.

Titan. (2022). *TITAN Cement Group: H2CEM project is included in the "Hy2Use" Important Project of Common European Interest.* Available at: https://www.titan-cement.com/wp-content/uploads/2022/09/26_09_2022_TITAN_Groups_H2CEM_project_is_included_in_the_Hy2Use_EN.pdf

Turboden. (2022). *Waste Heat Recovery*. Available at: https://www.turboden.com/solutions/1053/waste-heat-recovery

UNEP. (2017). *Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement based materials industry*.

UNFCCC. (2021). *CDM METHODOLOGY BOOKLET*.

UNFCCC. (2021a). *AM0121: Emission reduction from partial switching of raw materials and increasing the share of additives in the production of blended cement --- Version 1.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM0121

UNFCCC. (2021b) A*CM0003: Partial substitution of fossil fuels in cement or quicklime manufacture --- Version 9.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM0003

UNFCCC. (2021c) *ACM0005: Increasing the blend in cement production --- Version 7.1.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM0005

UNFCCC. (2021d) *ACM0009: Fuel switching from coal or petroleum fuel to natural gas --- Version 5.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM0009

UNFCCC. (2021e) *ACM0012: Waste energy recovery --- Version 6.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM00012

UNFCCC. (2021f) *ACM0015: Emission reductions from raw material switch in clinker production --- Version 4.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM00015

UNFCCC. (2021g) *ACM0021: Reduction of emissions from charcoal production by improved kiln design and/or abatement of methane --- Version 1.0.0*. Available at: https://cdm.unfccc.int/methodologies/view?ref=ACM00021

United Nations. (2003). *UN comtrade*.

USGS. (2002-2019). *Data for annual publication Minerals Yearbook, Cement, XLS Format, 2002 to 2019*. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

USGS. (2022). *Mineral Commodity Summaries 2022*. Available at: https://doi.org/10.3133/mcs2022

USITC. (1994). *Certain Calcium Aluminate Cement and Cement Clinker From France. Investigation No. 731-TA-645 (Final)* Available at: https://www.usitc.gov/publications/701_731/pub2772.pdf

UVP-Verbund. (2022). *Errichtung und Betrieb einer Pilotanlage zur Herstellung von Zementklinker mit einer Kapazität von 450 t/d nach dem Oxyfuel-Verfahren mit integrierter CO2-Abscheidung*. https://www.uvp-verbund.de/trefferanzeige?docuuid=F60E6F4C-45A8-4856-A509-E649417DCBA4&plugid=/ingrid-group:ige-iplug-bw&docid=F60E6F4C-45A8-4856-A509-E649417DCBA4

van Ekenstein, A. (2020). *Master thesis report. Towards circular cement: Evaluation of the reactivity of cementitious binder retrieved from recycled cement stone*.

van Oss, H. G., & Padovani, A. C. (2008). Cement Manufacture and the Environment: Part I: Chemistry and Technology. Volume6, Issue1, January 2002, Pages 89-105. https://doi.org/10.1162/108819802320971650

Vassiliko Cement. (2020). *VASSILIKO CEMENT WORKS PHOTOVOLTAIC PARK NOW LIVE*. Available at: https://www.vassiliko.com/en/investor-relations/announcements/announcements-2020/dispersion-of-share-capital1039

VEEP description. (2016). *Cost-Effective Recycling of CDW in High Added Value Energy Efficient Prefabricated Concrete Components for Massive Retrofitting of our Built Environment*. H2020 project nr: 723582. Available at: https://cordis.europa.eu/project/id/723582

VEEP project. (2016). Available at: http://www.veep-project.eu/

VEEP project del. 7.6. (2021). *D7.6 Report on the contribution to the Standardization system*. 31 March 2021. Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5db493d7a&appId=PPGMS

Vicat & Hynamics. (2021). *Vicat et Hynamics (EDF) dévoilent le projet Hynovi, pour la décarbonation du secteur cimentier et la production de méthanol décarboné*. Available at: https://www.vicat.fr/sites/www.vicat.fr/files/2021-09/Alerte%20presse%20Hynovi%20-%20090921%20finale_0.docx

Vicat. (2020). *Le groupe Vicat équipe sa cimenterie de Montalieu-Vercieu du dispositif CO2ntainer de Carbon8 Systems*. Available at: https://www.vicat.fr/sites/www.vicat.fr/files/2020-12/CP_VICAT_CARBON8.pdf

Vicat. (2021). *CimentAlgue: valorisation du CO_2 et de la chaleur fatale de cimenterie pour produire des microalgues.* Available at: https://www.vicat.fr/actualites/cimentalgue-valorisation-du-co2-et-de-la-chaleur-fatale-de-cimenterie-pour-produire-des

Vicat. (2021b). *Meteor: augmentation de la part de combustibles alternatifs à Montalieu-Vercieu*. Available at: https://www.vicat.fr/actualites/meteor-augmentation-de-la-part-de-combustibles-alternatifs-montalieu-vercieu

Votorantim Cimentos. (2021). *Declaración Ambiental 2020, Toral de los Vados*. Available at: https://www.votorantimcimentos.es/es-es/cementovt/Documents/Declaraci%C3%B3n%20ambiental%20%2B%20Anexo%20VII%20CEMENTOS%20COSMOS%20firmados.pdf

Wang, T., Yi, Z., Guo, R., Huang, H., Garcia, S., & Maroto-Valer, M. (2021). *Particle carbonation kinetics models and activation methods under mild environment: The case of calcium silicate*. Chemical Engineering Journal, Volume 423, 2021, 130157, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2021.130157.

WBCSD. (2013). *Technology Roadmap Low-Carbon Technology for the Indian Cement Industry*.

WCD. (2002). *World Cement Directory, 11th ed.*, Cembureau, 2002.

Westkueste100 project. (2019). *Holcim*. Available at: https://www.westkueste100.de/en/holcim/

WorldCement. (2014). *CO_2 Reducing Cement, Part One: Solidia Cement Composition and Synthesis*. Available at: https://www.worldcement.com/the-americas/09012014/co2_reducing_cement_part_one_solidia_cement_chemistry_and_synthesis_571/

WWF. (2008). *A blueprint for a climate friendly cement industry*.

Ylmén, R., & Jäglid, U. (2013). *Carbonation of Portland Cement Studied by Diffuse Reflection Fourier Transform Infrared Spectroscopy*. International Journal of Concrete Structures and Materials, 7, 119-125. https://doi.org/10.1007/s40069-013-0039-y

Zajac, M., Skocek, J., Bullerjahn, F., Lothenbach, B., Scrivener, K., & Ben Haha, M. (2019). *Early hydration of ye'elimite: Insights from thermodynamic modelling*. Cement and Concrete Research, Volume 120, 2019, Pages 152-163, ISSN 0008-8846, https://doi.org/10.1016/j.cemconres.2019.03.024.

Zapata, J. F., Azevedo, A., Fontes, C., Neves Monteiro, S., & Colorado H. A. (2022). *Environmental Impact and Sustainability of Calcium Aluminate Cements*. Sustainability 2022, 14(5), 2751; https://doi.org/10.3390/su14052751

ZEP. (2017). *CCS for industry - Modelling the lowest-cost route to decarbonising Europe*.

Zhutovsky, S., & Shishkin, A. (2021). *Recycling of hydrated Portland cement paste into new clinker*. Construction and Building Materials, Volume 280, 2021, https://doi.org/10.1016/j.conbuildmat.2021.122510

ZKW Otterbein. (2022). *Hintergrundinformationen zum Maßnahmenpaket "OTTERBEIN ZEMENT ECO-PLUS 2023"*. Available at: https://www.zkw-otterbein.de/nachbarschaftsdialog/hintergrundinformationen-otterbein-zement-eco-plus-2023

Additional reading:

BCG. (2013). *The Cement Sector: A Strategic Contributor to Europe's Future.*

Cembureau. (2017). *Innovation in the cement industry*.

Cembureau. *Building carbon neutrality in Europe Engaging for concrete solutions*.

Ciment Català. (2021). Catalan cement industry roadmap towards climate neutrality in 2050 - Cementing the European Green Deal.

Cembureau. (2022). *The European cement industry in numbers*. Available at: https://lowcarboneconomy.cembureau.eu/the-european-cement-industry-in-numbers/

CemSuisse. (2021). *Feuille de route 2050 - Objectif: ciment climatiquement neutre*.

CMI. (2014). *Building a sustainable future for Ireland*.

Fossil Free Sweden. (2021). *Roadmaps for fossil free competitiveness – follow-up 2021*.

Franklin Templeton thinks. (2021). *Global innovations driving zero-carbon cement.*

Holcim. *Our net zero roadmap*, https://www.holcim.com/our-net-zero-roadmap.

ICE & CLC/GCB/LCCG. (2022). *Low Carbon Concrete Routemap, Setting the agenda for a path to net zero*.

IFC. (2021). *Strengthening Sustainability in the Cement Industry*.

IISD. (2018). *Low-Carbon Innovation for Sustainable Infrastructure: The role of public procurement*.

MPA UK concrete. (2020). *UK Concrete and Cement Industry Roadmap to Beyond Net Zero*.

PCA. (2021). *Roadmap to carbon neutrality - A more sustainable world is Shaped by Concrete*.

Sandbag. (2017). *The Cement Industry of the Future - How border adjustment measures can enable the transition to a low-carbon cement industry*.

VDZ. (2021). *Dekarbonisierung von Zement und Beton – Minderungspfade und Handlungsstrategien. Eine CO2-Roadmap für die deutsche Zementindustrie*.

WBCSD. (2002). *Toward a Sustainable Cement Industry*.

WBCSD. (2011). *CO_2 and Energy Accounting and Reporting Standard for the Cement Industry*.

WBCSD/CSI. (2018). *Low Carbon Technology Roadmap for the Indian Cement Sector: Status Review 2018*.

List of abbreviations

2DS	2 Degrees Celsius Scenario
APBS	Amine-Promoted Buffer Salts
BAT	Best Available Techniques
bcm	billion cubic meter
BCSA	Belite-Ye'elimite-Ferrite Cement
BREF	Best Available Techniques Reference Document
BYF	Belite-Ye'elimite-Ferrite Cement
C&DW	Construction and Demolition Waste
C&IW	Commercial and Industrial Waste
CAC	Calcium Aluminous Cement
CaL	Calcium Looping
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCSC	Carbonatable Calcium Silicate Cement
CCU	Carbon Capture and Utilisation
CCUS	Carbon, Capture, Utilisation & Storage
CDM	Clean Development Mechanism
CDW	Construction and Demolition Waste
CSA	Calcium sulfoaluminate Cement
EIGL	Energy and Industry Geography Lab
EII	Energy Intensive Industry
ERA	European Research Alliance
ERDF	European Regional Development Fund
ETS	Emissions Trading System
GBFS	Granulated Blast Furnace Slag
GCCA	Global Cement and Concrete Association
GCD	Global Cement Directory
GHG	Greenhouse Gas
GVA	Gross Value Added
IEA	International Energy Agency
IHCal	Indirectly Heated Carbonate Looping
IPCEI	Important Projects of Common European Interest
IWG	Implementation Working Group
MOMS	Magnesium Oxides derived from Magnesium Silicates
MSW	Municipal Solid Waste
Mtoe	Million tonnes of oil equivalent
OPC	Ordinary Portland Cement
ORC	Organic Rankine Cycle
RDF	Refuse Derived Fuels
RDI	Research, Development and Innovation
RES	Renewable Energy Sources
RTS	Reference Technology Scenario
SILC	Sustainable Industry Low Carbon
SRF	Solid Recovered Fuel
SSC	Super Sulfated Cement
TRL	Technology Readiness Level
WCD	World Cement Directory
WHR	Waste Heat Recovery
ZEP	Zero Emissions Platform

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Annexes

The following annexes summarise cement-related projects encountered in Europe. Annex 1 looks into the evolution of EU funding, while annex 2 limits itself to ongoing corporate and nationally funded projects.

This include funding provided under the Sustainable Industry Low Carbon (SILC) initiative between 2011 and 2020 [European Commission, 2022f], i.e. projects FHRS for waste heat recovery and AETHER2 for alternative cement chemistry in SILC phase 1 (2011-2013).

However the overview of EU-funded Interreg projects available under KEEP.eu website is not exhaustive: relevant projects funded under this instrument may be missing in the list below, such as the SolCement and Carbongreen projects.

And projects funded under Horizon Europe are not yet accounted for. Project FLEXIndustries, for example, is such a project that may impact the cement industry.

Funding provided by Important Project of Common European Interest (IPCEI) calls have not been systematically assessed. In addition selected projects, already in the making, are not yet kicked-off:

- Project of Common Interest 12.9 in Poland for a EU CCS Interconnector, which includes cement operation [European Commission, 2021];
- Innovation funds projects Carbon2Business; ANRAV and GO4ECOPLANET, funded under call InnovFund-LSC-2021 [HeidelbergCement, 2022b; Holcim, 2022c; European Commission, 2022].

The European Investment Bank project "Sustainable cement RDI" provides EUR 167 million for reducing environmental and carbon footprint of cement facilities, as well as research, development and innovation activities, for the period 2021-2023. However the details of projects funded through this instrument are not available, therefore preventing the identification of cement related projects.

Finally, additional projects, especially if they concern alternative binders or concrete, may be found on Cembureau map of Innovation projects [Cembureau, 2022].

Annex 1. List of European funded projects towards cement decarbonisation

Project identifier	Acronym	Start Date	End Date	Total Cost	Heading
6350	GAIAboard	01/10/2011	31/03/2015	893 885	ALT. MATERIALS
9380	E*Zephyr 600	01/04/2015	01/04/2017	2 294 820	EFFICIENCY
299653	ANICA	01/09/2019	31/08/2022	2 400 000	CCUS
299663	AC2COM	01/09/2019	31/08/2022	4 273 911	CCUS
ERA-MIN-2018_77	RECEMENT	01/10/2019	30/09/2022	482 720	RECYCLING
MNET18/NMAT-3486	POLYWORK	01/01/2019	31/12/2019	500 000	ALT. MATERIALS
ERA-NET project	CEMENTEGRITY	01/10/2021	30/09/2024	2 000 000	ALT. MATERIALS
ERA-NET project	SCOPE	01/09/2021	31/08/2024	3 700 000	CCUS
214030	CODICE	01/09/2008	31/08/2011	3 757 240	OTHERS
218609	EURECOMP	01/05/2009	31/07/2012	2 549 233	ALT. FUELS
219062	POLYSTABILAT	17/10/2008	16/04/2015	7 563 452	ALT. FUELS
226898	ROCARE	01/09/2009	31/08/2012	2 109 572	OTHERS
230635	POSINAM	15/10/2009	14/10/2013	562 281	OTHERS

233469	IMS2020	01/01/2009	31/07/2011	2 860 930	OTHERS
235886	ADHCEM	01/01/2010	31/12/2011	181 351	OTHERS
246335	EDEFU	01/06/2010	31/05/2014	13 118 251	EFFICIENCY
256790	LOVE	01/10/2010	31/03/2014	5 061 352	EFFICIENCY
262019	HEATPOWER	01/01/2011	31/12/2012	1 322 992	EFFICIENCY
264448	TRANSCEND	01/10/2010	30/09/2014	4 036 120	OTHERS
265189	C2CA	01/01/2011	30/04/2015	4 918 490	RECYCLING
272653	DICEM	01/09/2011	28/02/2013	134 256	OTHERS
282856	RECOPHOS	01/03/2012	28/02/2015	4 533 275	ALT. MATERIALS
282922	ECO-CEMENT	01/03/2012	28/02/2015	2 138 511	ALT. MATERIALS
283077	IOLICAP	01/12/2011	29/02/2016	5 770 719	CCUS
285463	SUS-CON	01/01/2012	31/12/2015	7 128 681	ALT. MATERIALS
296010	LOCIMAP	01/12/2012	30/11/2014	2 523 632	OTHERS
298337	AMORPH	01/06/2012	31/05/2014	192 622	ALT. MATERIALS
299384	GEOSOX	01/08/2012	31/07/2013	134 548	OTHERS
309451	HEALCON	01/01/2013	31/12/2016	5 610 519	ALT. MATERIALS
314311	SUPREME	01/09/2012	31/08/2015	4 554 036	OTHERS
314636	DAPHNE	01/10/2012	30/09/2015	8 614 087	ALT. FUELS
314884	RESTAR	01/10/2013	30/09/2015	1 615 446	EFFICIENCY
314922	ALUSALT	01/11/2012	31/12/2014	1 504 378	ALT. MATERIALS
314991	ICARUS	01/08/2012	31/07/2014	1 422 302	EFFICIENCY
605748	LCE4ROADS	01/10/2013	31/12/2016	3 670 169	OTHERS
608524	GREEN-CC	01/09/2013	31/12/2017	8 137 278	CCUS
608578	SCARLET	01/04/2014	31/03/2017	7 349 129	CCUS
608893	H-House	01/09/2013	31/08/2017	6 550 894	ALT. MATERIALS
SI2.641287	FHRS	19/12/2012	19/09/2015	1235490	EFFICIENCY
SI2.666131	AETHER2	20/12/2013	19/06/2015	1186033.7	ALT. MATERIALS
636727	SAMT	01/01/2015	31/12/2016	514 804	OTHERS
636771	STYLE	01/01/2015	31/12/2016	497 516	OTHERS
636876	REDMUD	01/12/2014	31/10/2019	3 720 893	ALT. MATERIALS
637138	ECO-Binder	01/01/2015	31/12/2018	7 594 674	ALT. MATERIALS
637189	TASIO	01/12/2014	31/05/2019	3 989 248	EFFICIENCY
641185	CEMCAP	01/05/2015	31/10/2018	9 976 416	CCUS
642085	HISER	01/02/2015	31/01/2019	7 665 263	RECYCLING
642154	FISSAC	01/09/2015	29/02/2020	11 214 565	ALT. MATERIALS
642976	NanoHeal	01/01/2015	31/12/2018	4 103 573	EFFICIENCY
654465	LEILAC	01/01/2016	30/06/2021	20 970 635	CCUS
654663	SOLPART	01/01/2016	31/12/2019	4 558 688	ALT. FUELS
672421	Heat2Energy	01/05/2015	30/09/2015	71 429	EFFICIENCY
673527	VirtuCrete	01/07/2015	31/12/2015	71 429	ALT. MATERIALS
679386	EPOS	01/10/2015	30/09/2019	5 191 388	OTHERS
690088	METGROW PLUS	01/02/2016	31/01/2020	7 911 463	ALT. MATERIALS
699892	ECo	01/05/2016	30/04/2019	3 239 139	CCUS
721185	NEW-MINE	01/09/2016	31/08/2020	3 836 166	ALT. FUELS
721385	SOCRATES	01/09/2016	31/08/2020	3 858 940	ALT. MATERIALS

723670	REHAP	01/10/2016	31/03/2021	8 157 789	ALT. MATERIALS
723678	CarbonNext	01/09/2016	31/08/2018	495 748	CCUS
738759	SMARTSAND	01/12/2016	31/05/2020	1 155 764	ALT. MATERIALS
744548	C2B	01/01/2017	30/04/2017	71 429	CCUS
746830	Sewage Sludge in Portland Cement	01/03/2017	28/02/2019	134 462	ALT. FUELS
760431	BioRECO2VER	01/01/2018	31/12/2021	7 239 149	CCUS
760639	EnDurCrete	01/01/2018	31/12/2021	5 912 001	ALT. MATERIALS
760884	CARMOF	01/01/2018	30/06/2022	7 440 055	CCUS
760899	GENESIS	01/01/2018	30/04/2022	9 548 135	CCUS
760994	ENGICOIN	01/01/2018	30/06/2022	6 986 910	CCUS
761042	BIOCONCO2	01/01/2018	30/06/2022	6 999 886	CCUS
764816	CLEANKER	01/10/2017	31/03/2022	9 237 851	CCUS
768583	RECODE	01/08/2017	31/07/2022	7 904 415	CCUS
768772	ETEKINA	01/10/2017	31/03/2022	5 539 612	EFFICIENCY
768755	HARMONI	01/08/2017	31/10/2019	999 614	OTHERS
773577	ALSiment	01/05/2017	31/08/2017	71 429	ALT. MATERIALS
776469	RemovAL	01/05/2018	31/10/2022	14 658 966	ALT. MATERIALS
776846	NEMO	01/05/2018	31/10/2022	14 189 080	ALT. MATERIALS
777823	TRAC	01/07/2018	30/06/2022	450 000	RECYCLING
817251	ConcTest	01/06/2018	31/08/2018	71 429	OTHERS
820670	CIRMET	01/10/2018	30/09/2022	9 884 902	EFFICIENCY
820771	BAMBOO	01/09/2018	28/02/2023	15 900 520	EFFICIENCY
820783	DESTINY	01/10/2018	30/09/2022	8 442 000	ALT. FUELS
827343	CapCO2	01/10/2018	31/03/2019	71 429	CCUS
837754	STRATEGY CCUS	01/05/2019	31/07/2022	3 069 474	ALT. MATERIALS
837975	MOF4AIR	01/07/2019	30/06/2023	11 094 138	CCUS
838061	CO2Fokus	01/07/2019	30/06/2023	3 994 950	CCUS
838077	eCOCO2	01/05/2019	31/10/2023	4 447 979	CCUS
847097	SO WHAT	01/06/2019	30/11/2022	4 195 358	OTHERS
847121	EMB3Rs	02/09/2019	01/09/2022	4 245 119	EFFICIENCY
856282	Carbon8	01/02/2019	31/05/2019	71 429	ALT. MATERIALS
869886	HyperCOG	01/09/2019	28/02/2023	7 649 263	OTHERS
869939	RETROFEED	01/11/2019	31/10/2023	15 645 077	ALT. FUELS
876354	ngCon	01/07/2019	30/09/2019	71 429	ALT. MATERIALS
883395	WatFun	01/01/2021	31/12/2025	2 499 787	OTHERS
884170	LEILAC2	01/04/2020	31/03/2025	34 675 725	CCUS
893469	NEASCMs	02/08/2021	01/08/2023	224 934	ALT. MATERIALS
896824	NMRCement	01/09/2021	31/08/2023	190 681	ALT. MATERIALS
958208	ReActiv	01/11/2020	31/10/2024	10 594 926	ALT. MATERIALS
958267	FlashPhos	01/05/2021	30/04/2025	15 226 966	ALT. FUELS
958402	AI-CUBE	01/09/2020	31/08/2022	597 806	OTHERS
101009382	CemShale CemTower	01/10/2020	30/09/2022	2 168 142	ALT. MATERIALS
101009387	ngCon	01/11/2020	31/10/2022	3 595 000	ALT. MATERIALS
101022484	ConsenCUS	01/05/2021	30/04/2025	13 905 273	CCUS

101022487	ACCSESS	01/05/2021	30/04/2025	18 427 187	CCUS
101022831	CO2OLHEAT	01/06/2021	31/05/2025	18 813 891	EFFICIENCY
101038888	Silverstone	01/12/2021	31/12/2030	3 867 988	CCUS
101051358	K6	01/04/2022	31/12/2037	153 386 598	CCUS
INTERREG project	BNB - Beton naar hoogwaardig beton	01/03/2018	28/02/2021	3 549 175	RECYCLING
INTERREG project	Coat4Cata	10/01/2016	31/12/2019	1 325 011	OTHERS
INTERREG project	SeRaMCo	16/03/2017	15/06/2021	7 276 839	RECYCLING
INTERREG project	URBCON	25/10/2018	24/10/2023	5 202 446	ALT. MATERIALS
INTERREG project	CO2REDRES	15/07/2020	31/12/2022	1 246 590	ALT. MATERIALS
INTERREG project	ECO_2Flex	01/08/2020	01/08/2023	4 634 162	ALT. MATERIALS
LIFE09 ENV/FR/000595	AETHER	01/09/2010	31/08/2013	5 879 780	ALT. MATERIALS
LIFE11 ENV/CY/000859	QuaResE	01/06/2012	30/11/2014	911 228	EFFICIENCY
LIFE13 ENV/FR/000234	LIFE+ NOWASTHEM	01/06/2014	31/07/2018	8 914 400	ALT. FUELS
LIFE13 ENV/IT/000185	LIFE CARWASTE	01/06/2014	31/12/2017	2 346 103	ALT. FUELS
LIFE15 CCM/FR/000116	SOLID LIFE	15/06/2016	30/04/2019	3 830 320	ALT. MATERIALS
612429-EPP-1-2019-1-DE-EPPKA2-SSA-B	SAIS	01/01/2020	31/12/2023	3 954 198	OTHERS
749809 (2017)	ACTISLAG	01/07/2017	30/06/2021	2 880 451	ALT. MATERIALS
847260 (2019)	SLAGREUS	01/06/2019	30/11/2022	1 235 085	ALT. MATERIALS

Source: JRC

Annex 2. List of projects towards cement decarbonisation funded at corporate or national level

Project / Reference	**Technology**	**Country**
Carbon2Chem project [FONA, 2022]	CCU	Germany
[Catch4Climate, 2021]	CCU	Germany
[C^{2}inCO2 project, 2020]	Concrete carbonation	Germany
[C2PAT, 2022]	CCU	Austria
[CemZero project, 2018]	Electrification	Sweden
Clean Cement Line [SECIL, 2020]	Various	Portugal
[Concrete Chemicals project, 2021]	Synthetic fuel	Germany
[Decarbonate project, 2022]	Electric kiln	Finland
[ECRA, 2016b]	Oxyfuel	Austria & Italy
[Fastcarb, 2021]	Concrete carbonation	France
[GO4ZERO project, 2022a]	Decarbonised Obourg plant	Belgium
[GreenCem, 2020]	CCS	Denmark
[Greensand project, 2020]	CCS	Denmark
H2CEM project [Titan, 2022]	Hydrogen kiln	Greece
[Heatleap project, 2014]	Waste heat recovery	
[INDAVER project, 2022]	Alternative raw materials	Belgium
[K4 project, 2022]	Re-use of cement paste	Germany
[NGHV project, 2022]	Hydrogen	Portugal
REINCE project [Cementos Cruz, 2022]	Geopolymers	Spain
[Westkueste100, 2019]	Oxyfuel & synthetic fuel	Germany

Source: JRC

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