Support to Sino-German Cooperation on NDC Implementation:

Sectoral Best Practice

Review of technologies: Cement sector

Report for Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

ED 13426 | Issue number 4 (Final) | Date 30/09/2020

Customer:

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)

Customer reference:

81247609 (17.9017.9-001.00)

Confidentiality, copyright and reproduction:

Author:

Richard Hodges, Duncan Woods

Approved by:

Chris Green

Date:

30/09/2020

Ref: ED13426

Ricardo is certified to ISO9001, ISO14001, ISO27001 and ISO45001

Executive summary

Germany supports relevant programmes and projects in China through bilateral dialogue in the “Sino-German Working Group on Environment and Climate Change”. One focus of this cooperation is accelerating implementation of the NDC, including providing support on "low-carbon transition" for the Chinese economy and "capacity development on climate change related matters" for climate change authorities at provincial and municipal levels.

Industry accounts for the largest percentage of China’s energy use so the sector is a key focus for realisation of the national actions. Over the past 15 years there have been significant actions in Europe at national and Union levels to drive forward industrial decarbonisation. There is an opportunity to draw on this experience in Europe to identify best practices for industrial decarbonisation policies and technical measures. This report focuses on technical measures available for reducing carbon dioxide (CO_2) emissions from cement production.

An overview is provided of the European cement industry, describing the sector’s contribution to the economy, an overview of the production process, energy use and emissions sources, and issues faced by the sector in relation to transitioning towards decarbonisation. Cement production is one of the top three CO_2 emitting energy intensive industries. As a relatively low value product there are significant financial barriers to investment in decarbonisation techniques, meaning the sector would particularly benefit from additional support or incentives to facilitate transition. Furthermore, despite the low value of cement, the sector is important for local economies, as it is a high employer and key supplier of materials for construction which are not suited for transport over long distances.

The main focus of this study is on technical options that are commercialised in Europe and which could be implemented within the next five years in China. A review of state of the art techniques shortlisted five measures:

- Using raw meal with lower calcium carbonate content
- Using mineralisers to promote clinker formation at lower temperatures
- Switching from coal to waste or biomass fuels
- Adding pre-calciners and multi-stage pre-heaters to kilns
- Recovering heat from kiln or clinker cooler to generate electricity

A description is provided for each measure, detailing the applicability, impact on energy consumption and CO_2 emissions, costs, barriers to uptake and interaction with other measures. Together, the measures have the potential to reduce emissions by up to 20%, depending on the existing status of the cement works to which they are fitted. A high-level approximation of the possible implication for the Chinese cement sector indicates an emissions reduction potential of up to 14% through take up of these measures.

The technical measures focus on reducing the emissions intensity of cement production. A further option to reduce emissions from the sector is to reduce production, by reducing demand for cement. A section on the circular economy implications for the sector describes the use of substitutes during the cement production process, as well as extending longevity of concrete structures, options for recycling, and building codes as a way to encourage embodied emissions reduction in the construction sector.

In the longer term, carbon capture and utilisation or storage (CCUS) is needed to abate the unavoidable process emissions from clinker production. The status of European research and development projects on CCUS in the cement sector are described, detailing the main techniques for CO_2 capture as well as EU developments and legislation for transport and storage. Utilisation of CO2 captured from the cement sector has been found to have limited potential.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

1.1 Context

Nationally Determined Contributions (NDCs) are a central part of the Paris Agreement (PA). China submitted as its first NDC in 2016 the 2015 INDC document, which is aligned with national policies and measures in its 13th Five Year Plan (FYP). This includes actions to: achieve peak carbon dioxide emissions around 2030; lower carbon dioxide emissions per unit of GDP by 60% to 65% from the 2005 level; and to increase the share of non-fossil fuels in primary energy consumption to around 20%.

Germany supports relevant programmes and projects in China through bilateral dialogue in the “Sino-German Working Group on Environment and Climate Change” (WG). Currently, one focus of this cooperation is accelerating implementation of the NDC, including providing support on "low-carbon transition" for the Chinese economy and "capacity development on climate change related matters" for climate change authorities at provincial and municipal levels. Key time horizons for consideration are therefore 2025 acknowledging that quick wins and earlier actions will have longer term benefits.

Industry accounts for the largest percentage of China’s energy use (62% in 2017, BP 2019), so the sector is a key focus for realisation of the national actions. Indirect impacts can also be significant, for example due to energy sector emissions associated with industrial electricity consumption. There could potentially be a variety of opportunities, such as retrofitting technologies or fuel switching.

Over the past 15 years there have been significant actions in Europe at national and Union levels to drive forward industrial decarbonisation. This includes, for the heavy emitting sectors, the introduction of the EU emissions trading system (ETS) and free allocation mechanism based on benchmarks for best performance of CO_2 emissions intensity, functioning alongside energy efficiency and renewable energy commitments, for example via the Energy Efficiency Directive (2012/27/EU and 2018/2002/EU) and Renewable Energy Directive (2009/28/EC and 2018/2001/EU). There have additionally been national and sectoral initiatives, roadmaps, policies and measures to identify and implement industrial decarbonisation.

There is an opportunity to draw on this experience in Europe to identify best practices, as well as the associated economic, political and social dimensions, for industrial decarbonisation policies and technical measures.

1.2 Objective

The objective of this study is to prepare capacity building materials and engage with relevant partners to support the question of: **“How to organize the low carbon transition in selected heavy emitting industries in China and what technical best practices exist?"**.

The aim of this project is to provide an overview of the EU situation, which will be used to identify and share examples of good practice for consideration in China. Providing an understanding of the spectrum of options in Europe can be used to inform suggestions for options for (packages of) measures at national and provincial level in China as a mechanism for industry transition to accelerate realisation of the NDC commitments.

The main task is to compile sector overviews and example technologies which may be applicable for enabling industrial transition to decarbonisation, drawing from European best practice. This information will feed into capacity building material for Chinese climate change authorities.

1.3 Sector selection

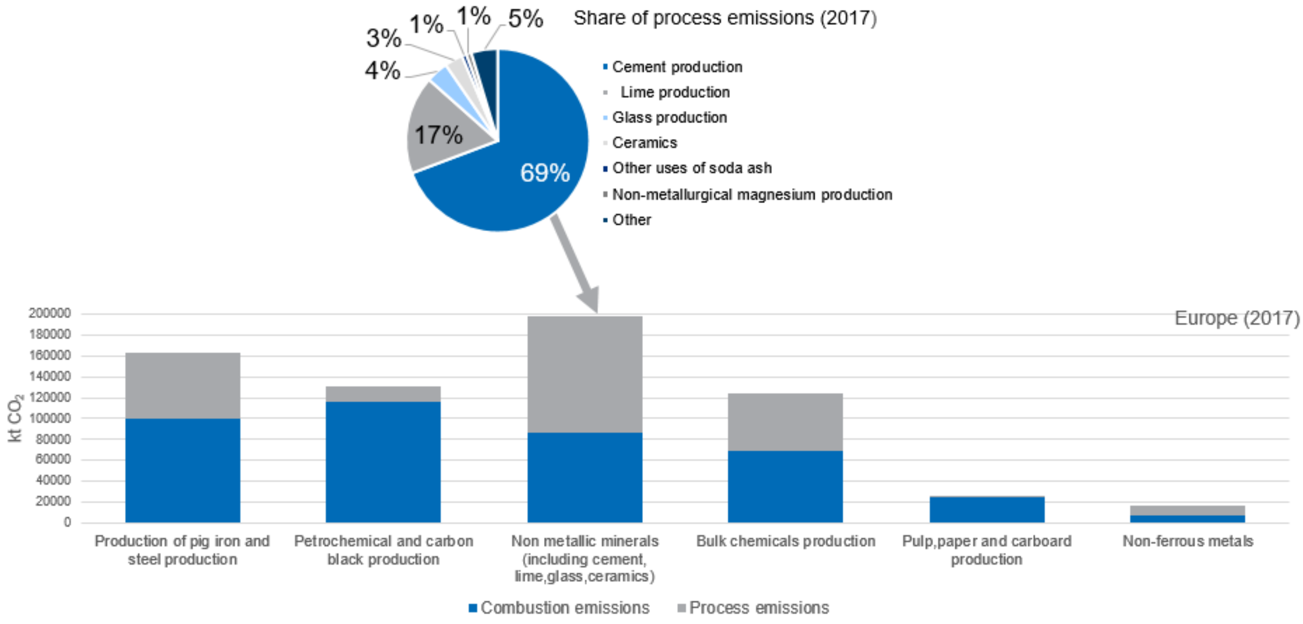
To inform discussion on the selection of sectors on which to focus, an assessment of European energy intensive industries has been made against the following criteria:

- Contribution to total EU emissions;
- Potential for reducing emissions intensity, within a five-year implementation period;
- Socio-economic significance:
    - Value added, as an indicator of contribution to GDP;
    - Employment; and
    - Composition of sector (number and size distribution of firms).

Following this assessment, cement production has been selected as the focus for the further analysis.

Non-metallic minerals production is the highest emitting industry sector within the EU, and within this, cement production is the main contributor, as shown in Figure 1.

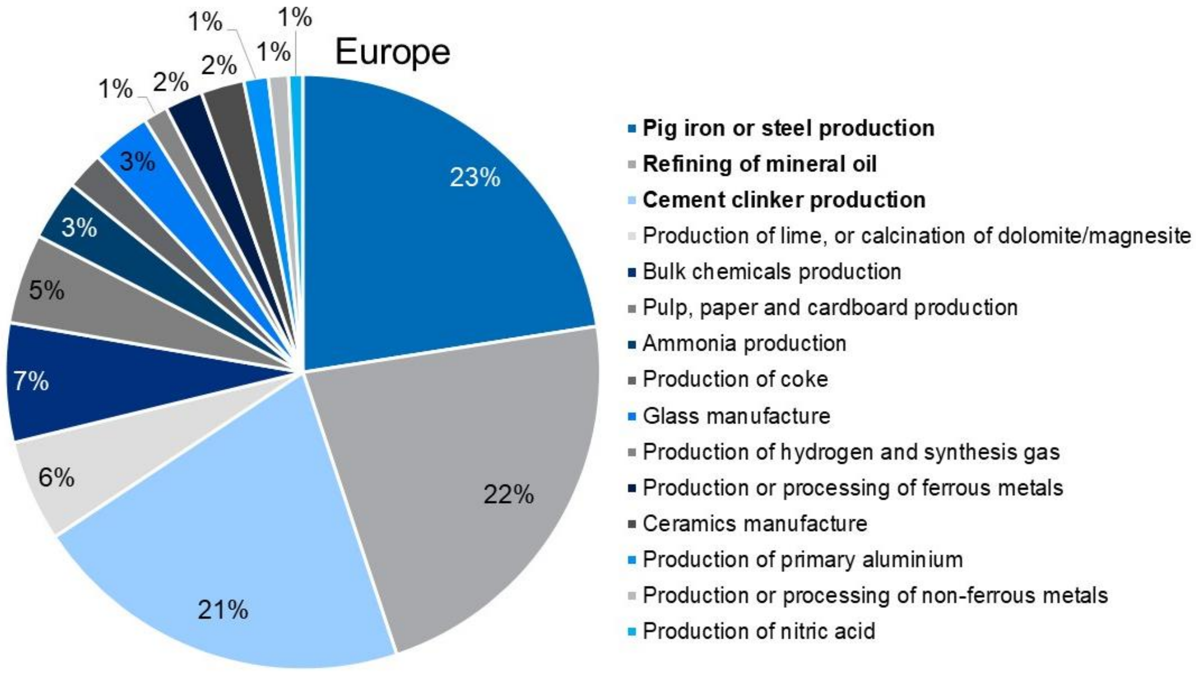
Figure 1 Annual CO_2 emissions from EU industry sectors



Source : UNFCCC Data, from 2019 submission of Europe's emissions inventory (2017)

Further disaggregation of sectors confirms cement production as one of the highest emitting sectors, as shown in Figure 2.

Figure 2 Annual average CO_2 emissions by EU ETS sector



Source : EEA (2020) EU ETS transaction log (EUTL) data viewer.

Note: annual average CO_2 emissions calculated for time series 2012 – 2018
Sectors representing < 1% of the share of CO_2 emissions are not visualised for simplicity
Does not include installations reporting under the main activity of "combustion of fuels".

In addition to these direct emissions, cement production also gives rise to indirect emissions due to electricity consumption. In Germany, these indirect emissions represent around 15% of the direct emissions from cement production[1].

An initial literature review identified a variety of commercially available techniques for reducing CO_2 emissions with examples of successful implementation within Europe, but which are not yet commonplace. Techniques were identified for all sectors. Limitations were identified for emission reduction potential in mineral oil refining as the emissions are significantly influenced by the final product mix and quality standards for those outputs, which is driven by demand and legislative standards. For this reason, the refining sector was not considered further.

Cement production is a concentrated sector with high average number of employees per company, meaning it is significant for local economies despite the relatively low value added of production. The low gross value added (GVA)[2] can be a barrier to commercial investment and indicates that external financial support could be well targeted to support action that may not otherwise happen. This is in contrast to sectors such as metals and chemicals production for which high GVA per unit of CO_2 emissions indicates there may be better potential for companies to absorb costs of investing in decarbonisation technology[3].

---

[1] European Commission, 2015, Study on the Impacts on Low Carbon Actions and Investments of the Installations Falling Under the EU Emissions Trading System (EU ETS)

[2] Value added represents the difference between the value of what is produced and consumption entering the production, less subsidies and taxes. Conceptually close to Gross domestic product (GDP), but unlike GDP is available per economic activity.

[3] There are also many other factors that influence investment decisions by companies.

2 The European cement industry

2.1 Overview

There are around 60 companies in the European cement sector, with six large international cement producers and other, smaller national and regional producers represented. The six international companies are the most important in terms of the scale of their operations, as they operate circa 60% of European cement sites; these are, in order of the number of sites: Lafarge Holcim Ltd (52 sites); Heidelberg Cement AG (36); Italcementi Group (36); CRH PLC (27); Buzzi Unicem SpA (23); and Cemex (20). By contrast national producers typically operate 1 to 4 sites each, whilst regional producers may operate 6 to 8 sites each; for example, 'Grupo Cementos Portland Valderrivas', which has a total of 8 sites in the Netherlands, Spain, Tunisia and UK.

In total there are circa 330 European sites producing cement; of these, 230 are integrated plants producing both clinker and cement on the same site, and a further 100 are grinding plants that manufacture cement from clinker brought in from elsewhere. There is only 1 standalone clinker plant in Europe. All of the priority decarbonisation techniques discussed in Section 0 are related to pyro-processing leading to the production of clinker and so are relevant to both integrated and standalone clinker sites. Most integrated plants, and therefore cement production, are located in just seven countries: Italy (35), Spain (35), Germany (34), France (30), Poland (13), UK (11) and Austria (9).The majority of cement grinding plants are located in: Italy (25), France (21), Germany (16), UK (6), Belgium (5) and Spain (5)

The majority (circa 85%) of European clinker production goes directly into the manufacture of cement (NACE 23.51). Some is also sold to other European producers, or is exported outside of Europe, or is stockpiled by producers for cement production at a later date.

2.2 Relative importance to EU economy

In 2017 circa 49,000 people were employed in the cement manufacturing industry within the EU; the sector contributed an estimated euro 17.088 billion in turnover and euro 5.329 billion in gross value added (GVA)[4]. Value added and contribution to GDP is relatively small, which reflects the high energy costs and low product price. However, cement production is economically significant due to its role in supplying construction and infrastructure, directly or as a feedstock for the production of higher value concrete products.

Cement is a high density, low value product and therefore transport costs are relatively high which results in low levels of long-distance trade. Overall EU trade intensity[5] for cement is only 7%[6]. Cement production is therefore significant for the local economy. Furthermore, production is concentrated in large facilities, with the highest average number of employees per company of energy intensive industries. Large firms have a geographically concentrated workforce, which can lead to significant direct and indirect regional impacts if closure occurs.

There is also concentration of production within the EU, where collectively just six countries – Belgium, France, Germany, Italy, Poland and Spain – accounted for circa 78% of turnover in the sector and circa 74% of employment[4].

---

[4] Eurostat. Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E). Data for cement sector. See: https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do
[5] Value of imports from and exports to non-EU countries in relation to the domestic market (domestic production + imports)
[6] Ecorys etal, 2013, Carbon Leakage Evidence Project. Factsheets for selected sectors

2.3 Types of product produced

Cement is commonly used for construction and is a relatively homogenous product (circa 80% of production is a single type ‘Portland cement’), hence, cement producers mostly compete on price on this product. Other more specialised types of cement with a range of chemical and physical properties are also produced for different applications – these have a higher value added and can also be exported.

Limestone is the main primary raw material used, followed by other raw materials containing silica, iron oxide and alumina. Secondary cementitious materials can also be used to substitute for the cementitious material produced by burning these raw materials. Examples of these include fly ash, ground granulated blast furnace slag (GGBS), limestone fines and silica fume.

Cement production involves two stages. In the first stage, a cement ‘clinker’[7] is produced by the calcination of limestone to produce lime (Ca) and subsequent heating and reaction of this lime with other materials, such as clay, bauxite, alumina, iron oxides, fly ash or blast furnace slag, as deemed necessary to achieve the final desired chemical composition This is achieved at very high temperatures within a cement kiln at very high temperatures. The result of this is a product known as “clinker “which is composed of a range of mineral phases, predominantly calcium silicates. In the second stage, the resulting clinker ‘intermediate’ product is finely ground in a grinding mill and mixed with other additives to produce the final cement product.

Cement clinker production in Europe is mostly grey cement clinker, but a small amount of white cement clinker (circa 1%)[8] is also produced for specialist architectural applications. The difference in colour is primarily a result of the different raw materials used, but higher temperatures are also required for white cement clinker.

Different types of cement are produced from different proportions of cement clinker in combination with other materials; for example, Portland cement typically comprises 95% cement clinker along with 3-5% gypsum and other additives.

The European standard (EN 197-1) for common cement identifies 27 different cement types, which are consolidated into five groups ‘CEM I to CEM V’. These groupings are further aggregated by Eurostat’s ‘production of manufactured goods’ (‘Prodcom’) data classification into three product categories that are manufactured. These are:

- **Cement clinker** – Prodcom code 23511100 – this category covers the manufacture of all types of cement clinker, both grey and white cement clinkers.
- **Portland cement** – Prodcom code 23511210 – this category covers the manufacture of both CEM I group – Ordinary Portland cement or ‘OPC’ (95% clinker, 3-5% gypsum) and CEM II group - other Portland composite cements (65-94% clinker combined with other cementitious components).
- **Other hydraulic cements** – Prodcom code 23511290 – this category covers the manufacture of all other types of hydraulic cement i.e. CEM III group - ‘Blast-furnace cement’ (5-64% clinker, with the other main component being blast-furnace slag), CEM IV group - ‘Pozzolanic cement’ (45-89% clinker, along with either silica fume, or pozzolana, or fly ash) and CEM V group - ‘Composite cement’ (20-64% clinker, with other components) and other special cements.

In terms of approximate relative outputs, in 2015 the CEM I group cement made up circa 56% of total cement production and is commonly used in construction for making concrete (composed of cement and an aggregate); CEM II group Portland composite cements comprise another 31% of production

---

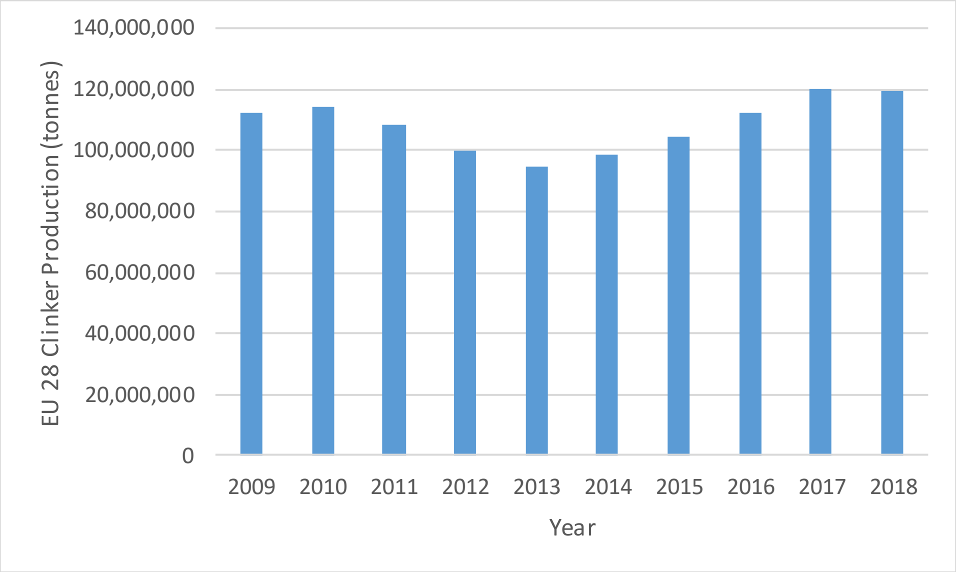
[7] A clinker is a nodular material ranging 1-25mm in size, produced in a cement kiln, which has to be finely ground to produce cement.
[8] White cement clinker for use as main binding component in the formulation of materials such as joint filers, ceramic tile adhesives, insulation, and anchorage mortars, industrial floor mortars, ready mixed plaster, repair mortars, and water-tight coatings. WBCSD (2009) The Cement Sustainability Initiative

and are also used in construction, but typically have slower hardening times compared to OPC. Other hydraulic cements make up the balance, with CEM III group Blast-furnace/slag cement 10%, CEM IV group Pozzolanic group 1-2% and CEM V group composite cements another 1-2% of total production[9].

2.4 Output, including historical trends

Output from the cement sector is measured by Eurostat in two ways: firstly, as the total annual volume in tonnes of cement clinker produced; and secondly, the total annual sold volume in tonnes of final products such as Portland cement and other hydraulic cements, as well as sales of intermediate cement clinker product to other cement producers with standalone grinding mills. The levels of clinker production within the EU28 over the last 10 years are shown in Figure 3.

Figure 3 Clinker production within the EU28 countries in the last 10 years



In terms of cement clinker production, Prodcom data for 2018, which is the most recent data available published by Eurostat[10], identifies Germany as the largest producer of clinker in the EU (19% total), closely followed by Spain (18%), then Poland (12%), Italy (11%), and France (11%).

Total annual clinker production increased by circa 6% from 2009 to 2018, from 112m to 120m tonnes. Comparative data on an EU28[11] basis is not available for production before 2009, so the impact of the 2008 financial crash is not easy to quantify. However, other data published by WBCSD Cement Sustainability Initiative from industry surveys suggests substantially higher average historical production levels of clinker of around 180m tonnes per year within the EU from 2000 to 2008.

Eurostat data for sales of cement products in 2007 was 268m tonnes, in comparison to which sales of 177m tonnes in 2018 (of which 83% was Portland cement) represent a 34% reduction on pre-financial crash levels. The long-term effect of the 2008 financial crash on the sector has been greatest for sales of Portland cement, with annual sales ranging from -24% to -35% below pre-crash levels, whilst annual sales of other hydraulic cements range from -8% to -14% below pre-crash levels.

---

[9] EC (2017) Competitiveness of the European Cement and Lime Sectors, p.21. See: https://www.wifo.ac.at/jart/prj3/wifo/resources/person_dokument/person_dokument.jart?publikationsid=61003&mime_type=application/pdf

[10] Eurostat Prodcom data for 2018. See: https://ec.europa.eu/eurostat/web/prodcom/data/excel-files-nace-rev.2

[11] Prodcom data for 2018 is on a European Union 28 (EU28) basis i.e. includes UK production data.

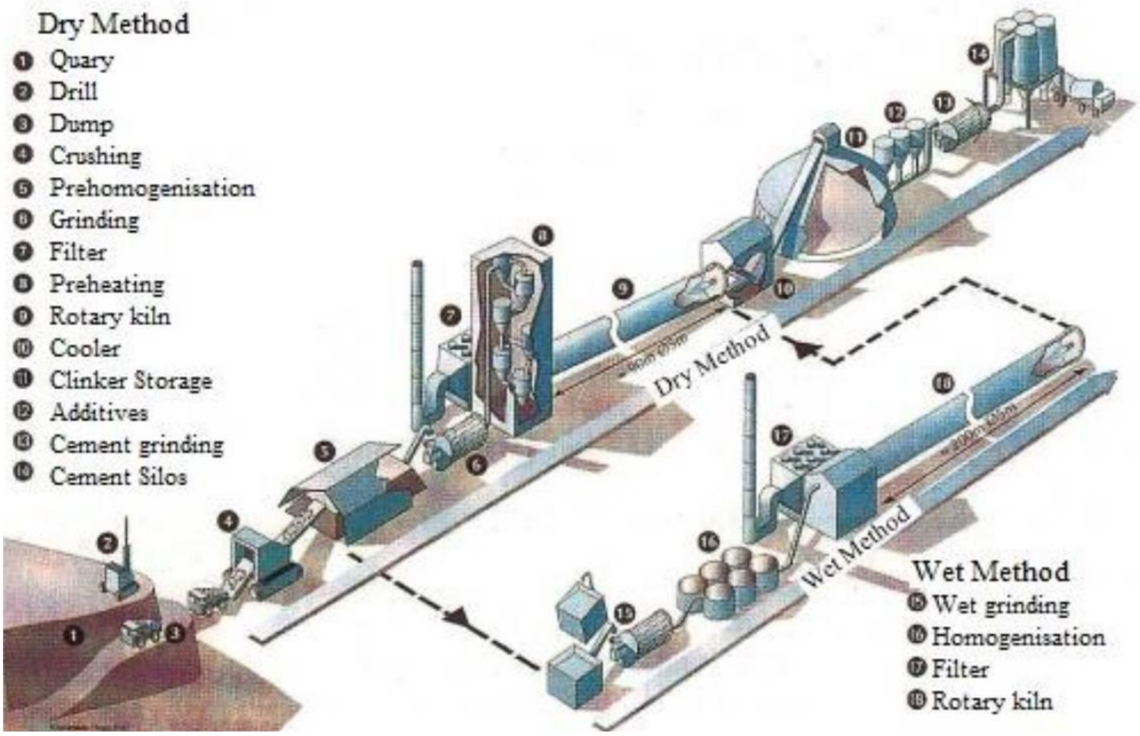
In comparison, annual sales of clinker to other cement manufacturers (13% in 2018) has increased slightly in most years since 2008, in a range from +14% to +40% above pre-crash levels. The reasons behind some of this increase may include the running down of stocks built up during the aftermath of the financial crash, as well as an upper limit on the market share for some larger producers, and greater demand for clinker from smaller competitive national producers. However, as the volumes of clinker sold are still comparatively low, this trend is not particularly significant.

There is hardly any import of clinker or cement from non-EU countries, whereas extra-EU exports of Portland cement are around 5% of total production. The trade balance with the rest of the world has been positive for every year between 2006 and 2015.

2.5 Overview of Production process

Cement production can be grouped into four main process steps – raw materials extraction, processing, clinker production, followed by grinding and blending. The type of cement kiln system used – dry, wet or intermediate – is to a large extent determined by the moisture content of raw materials being processed. In Europe almost all production is based on less energy intensive dry kiln systems[12]. A schematic diagram of the complete process from quarrying to product storage is shown in Figure 4 and described below.

Figure 4 Schematic of the cement production process at an integrated site



Source: EU MERCI[13]

---

[12] Typically used where raw materials have a moisture content of less than 20%. In Europe in 2007 90% of kilns systems were dry, with a further 7.5% intermediate (semi-dry or semi-wet). Ricardo understands wet kilns systems have now all been phased out.

[13] EU MERCI, Technical analysis –Cement sector, http://www.eumerci.eu/wp-content/uploads/2018/01/Cement.pdf

- **Raw materials extraction**: the main constituent is calcium carbonate containing materials such as limestone or chalk, which is quarried (1), crushed (4) and then conveyed to the cement plant, which is usually located nearby. Other raw materials used include sand, clay, bauxite and iron ore. Together these raw materials produce the non-metallic calcium alumina silicates and ferrite phases which make up cement clinker. Wastes are also used and can substitute for quarried material, such as blast furnace slag, silica fume etc. For white cement clinker production, pure raw materials with low metal oxide content are required.
- **Processing**: In dry kiln systems the raw materials are ground and dried (6) using recycled kiln gases to produce a homogenised powder called ‘raw meal’. The fineness and particle size distribution of the product leaving a ‘raw’ grinding system is tightly controlled.
- **Clinker production**: This step requires the calcination of limestone to form calcium oxide, and subsequent reaction with the other raw material constituents to form cement clinker. Dry and semi-dry kilns systems include the following process stages: pre-heating, pre-calcining, calcining and clinker reacting:
    - **Preheating**: the powdered raw meal is preheated in a counterflow with hot exhaust gases recycled from the rotary kiln, before the meal enters the kiln (8). This optimises heat recovery, reducing the amount of fuel required and so improves process efficiency. Suspension preheater systems comprise between four and six successive cyclone stages, arranged one above the other in a tower 50–120 m high. Preheating. can accomplish 30% of calcination due to the high temperature of the exhaust gases.
    - **Pre-calcination**: this takes place in a special combustion chamber (a ‘pre-calciner’) that connects the preheater to the rotary kiln. Fuel is burnt to further calcine the meal, which is circa 90 to 95% calcined by the time it enters the rotary kiln. The calcined meal leaves the calciner at between 850°C to 870°C.
    - **Clinker production**: the pre-calcined meal is fed into the rotary kiln. The calcined meal is burnt and sintered, under oxidising conditions and at temperatures of circa 1450°C, into clinker as it moves down the length of the rotating kiln (9). Primary fuel combustion occurs in the kiln burning zone where fuels - coal, petroleum coke, natural gas, fuel oil and alternative fuels – are fired directly into the kiln. Flame temperatures are required to reach 2000°C to maintain temperatures in the sintering zone at between 1400°C and 1500°C[14]. The flame shape can also be controlled using primary combustion air. This part of the process is the most important in terms of emissions reduction potential and control of cement quality and production cost.
    - **Cooling**: the clinker is rapidly cooled with air down to 100-200°C and is then stored (10). This rapid cooling is necessary to ensure that the desired mineralogical phases are preserved in the clinker and also to aid grinding.
- **Blending & Grinding**: cement clinker is mixed with other cementitious materials (12) and is ground (13) to produce a range of different types of cement such as OPC, composite or blended cements, before storage, typically in silos (14).

Process emissions largely arise in the pre-heating and pre-calcination stages described above, when the carbonates present are broken down to oxides and carbon dioxide (CO_2)[15]. Fuel combustion emissions arise primarily in the pre-calcination and clinker production stages and largely comprise CO_2, sulphur oxides (SOx), nitrogen dioxides (NO_X), as well as carbon monoxide (CO), volatile organic compounds (VOCs) and particulates (PM_{10}). CO_2 is the only greenhouse gas emitted and comprises the overwhelming majority of these emissions. The other pollutants affect air quality; certain technical measures targeted at reducing CO_2 emissions may have the co-benefit of reducing

---

[14] For white cement production, the firing process leads to temperatures in the sintering zone of up to 1600°C, depending on the composition of the raw material mix and the desired composition of the final product. Flame temperatures of higher than 2000°C are required because of the absence of fusing elements in the raw materials which could alter the colour of the product.

[15] Process emissions are usually calculated based on the amount and calcium and magnesium oxide of the clinker produced. Process emissions may also include sulphur oxides (SOx).

air pollutant emissions, or in a few cases may increase those emissions. There are other technical measures available which are targeted at controlling emissions of air pollutants.

2.6 Energy consumption in the process

Cement production is an energy intensive process and energy typically accounts for 40% of the total cost to produce a tonne of cement. Electricity and fuels supply the energy required for cement manufacture. 90 to 150 kWh of electricity is required per tonne of cement to run the grinding plant, fans and other electrical auxiliaries, which makes up circa 20% of the overall energy requirement. The clinker process' thermal energy demand is supplied by fuels.

A range of solid, liquid or gaseous fossil fuels are used to supply the thermal energy demand, such as petroleum coke, lignite/coal, natural gas and fuel oil. In addition, the European cement sector has switched where possible from fossil fuels to alternatives such as wastes or biomass. The theoretical thermal energy demand for cement clinker production is determined by the energy required for the chemical reactions of the clinker burning process (1650 to 1800 MJ/tonne clinker) and the thermal energy required for raw material drying and preheating, which mainly depends on the moisture content of the raw material[16]. Depending on the moisture content of raw materials, a thermal energy demand of about 200 to 1,000 MJ/t clinker (equal to a moisture content of 3 to 15%) is required for raw material drying. As a consequence, a theoretical minimum energy demand of 1,850 to 2,800 MJ/t clinker is set by chemical reactions and drying[17]. Typical energy consumption of plants using the dry kiln systems ranges from about 3000 to 3800 MJ/tonne clinker[18]. Therefore, the thermal energy efficiency (expressed as used energy related to energy input) of cement kilns is very high compared to many other industrial processes.

Electrical energy is mostly consumed by grinding plant (both raw and cement mills) and exhaust fans, which together account for circa 80-90% of total electrical energy usage[19]. Dry kiln systems require the raw meal to be finely ground, and fine grinding of clinker is required for good strength development in cement. Total electricity demand typically ranges from 90 to 150 kWh/tonne cement; of this, raw material extraction, fuel grinding and cement packing together consume circa 6-7%; raw material preparation 25%; clinker production 25%; and cement grinding circa 43%[20].

2.6.1 State of art levels of electricity and fuel consumption, combustion and process emissions

The efficiency of different cement plants can vary considerably depending on the type of process used, age and size of plant, raw material characteristics, fuel mix used and type of cement product produced. New kilns will obviously be more efficient and are being built with higher capacities, especially in new markets, leading to economies of scale. Existing plants can be retrofitted with new technologies, but this may require considerable investment. New European plants have throughputs in the range 3000 to 6000 tonnes clinker per day, although much larger plants are technically possible, with some new plants reportedly being built elsewhere with capacities of 10000 tonnes clinker per day.

For new state-of-the art dry process plants, five or six cyclone preheater stages with a pre-calciner are now considered standard and could give a specific fuel energy consumption of 3,000 to 3,400

---

[16] Best Available Techniques (BAT) Reference Document for the Production of Cement: Industrial Emissions Directive 2010/75/EU:(IPPC). See: https://ec.europa.eu/jrc/en/publication/reference-reports/best-available-techniques-bat-reference-document-production-cement-lime-and-magnesium-oxide
[17] European Cement Research Academy (ECRA). A-2016/2305. CSI/ECRA-Technology Papers 2017. Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead. See: https://ecra-online.org/fileadmin/redaktion/files/pdf/CSI_ECRA_Technology_Papers_2017.pdf
[18] BAT reference document.
[19] BAT reference document.
[20] ECRA refence document.

MJ/t clinker[21]. Whilst a higher number of cyclones (raw material characteristics permitting) enables greater heat transfer from outgoing kiln gas to incoming raw meal, this also entails a trade-off with the build-up of deleterious elements from the kiln gas, and so a kiln gas bypass may also be added to the pre-calciner to ensure continuous plant operation. This can be a particular problem when fuels containing traces of chlorine are used, as is the case with biomass and waste fuels. Modern burner types that can burn a range of different fuels including alternative fuels, and that can adjust flame characteristics within the kiln, are also widely used in the European cement sector.

Given grinding consumes most of the total electric energy demand, new cement grinding technologies are considered state-of-the art, for example, by replacing existing ball mills with more efficient vertical or high-pressure roller mills for cement grinding.

However, state-of-the-art environmental abatement, required by regulation, may also increase electrical demand. Lower dust emission limit values and abatement of other pollutants (like NO_X or SOx) tends to increase electricity demand; for example, the use of selective catalytic reduction (SCR) technology for NO_X abatement results in an increase in electrical energy demand of 5 kWh/t clinker[22].

2.6.2 Decarbonisation techniques

The focus of the research is to identify techniques which have the technical potential for implementation within five years and therefore have been successfully demonstrated at full scale or are already commercialised (i.e. TRL 8 or 9).

Box 1. Technology Readiness Levels (TRL)

TRL is a widely used rating system to classify the status of development of technologies progressing through nine steps from conceptualisation to commercialisation. The following definitions have been adopted for use under HORIZON 2020[23] (an EU innovation support fund).

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

A literature review identified the following list of commercially available techniques that represent best practice for reducing CO_2 emissions associated with cement production. These techniques are adopted at varying levels across EU production facilities. The options represent a variety of changes that can be made to different aspects of the production process.

---

[21] BAT and ECRA reference documents. State of the art – for 3 cyclone stages: 3,400 to 3,800 MJ/t clinker; 4 cyclone stages: 3,200 to 3,600 MJ/t clinker; 5 cyclone stages: 3,100 to 3,500 MJ/t clinker; and 6 cyclone stages: 3,000 to 3,400 MJ/t clinker.
[22] ECRA refence document.
[23] European Commission, 2019, Decision C(2019)4575 Horizon 2020 Work Programme 2018-2020, General Annexes

Feedback from a Chinese specialist highlighted that a number of these techniques are already adopted in China Table 1 shows the full list of techniques that were considered and distinguishes between those that were taken forward for further consideration and those that were not.

Table 1 Decarbonisation techniques for cement production

Option	Brief Option Description
Techniques selected for further investigation and further described in Section 0.	
Lowering the Calcium Carbonate Content of Raw Meal (Lowering the Lime Saturation Factor)	Reduction in the amount of calcium carbonate in the raw meal leads to less calcination CO_2 per unit mass of clinker produced. It also produces a raw meal with better burnability which, therefore, means lower burning temperatures and fuel savings. Clinker thus produced has a lower alite composition and this lowers early strength of the concrete, which will be a disadvantage in a number of applications. This lower early strength can be ameliorated by grinding the clinker to a higher degree of fineness, but this implies a higher grinding energy penalty.
Improvement in raw meal burnability	The addition of mineralisers to the raw meal promote the formation of clinker at lower temperatures. Some mineralisers also lower the dissociation temperature of calcium carbonate, thereby lowering the energy requirement for calcination. The availability and cost of suitable mineralisers may be a barrier to adoption of this option and the grindability of clinker may deteriorate, leading to increased electricity consumption.
Adopt preheaters and precalciners	Kilns with cyclone preheaters (3 to 6) and precalciners are State of the Art (SoA). These improve the thermal efficiency of clinker production by increasing the calcining efficiency by using exhaust gases to dry and preheat the raw meal. Existing kilns may have no or only single stage preheaters and/or precalciners.
Use of Alternative Fuels (with biogenic content) in Cement Kiln	Using waste or biomass as the kiln fuel instead of coal (or pet coke) reduces the combustion related CO_2 emissions from the clinker burning process, since these are lower carbon fuels. However, the extent of substitution with these fuels is limited for technical reasons, such as alternative fuel calorific value and the presence of undesirable trace elements such as chlorine. The lower calorific values of biomass and waste fuels mean that the level of substitution in the main kiln burner is limited, but the lower process temperatures in the pre-calciner mean that higher levels of alternative fuel substitution can be achieved in this part of the kiln system. The energy requirement typically increases with the use of these alternative fuels due to higher moisture contents. In 2016, biomass accounted for 15% and non-biogenic or mixed wastes for 30% of fuel use in EU cement production[24].
Recovery of Heat from Kiln and Clinker Cooler	Feasibility depends on the moisture content of raw material. Where this is high, there will be less surplus heat available for generating power via these routes.
Techniques considered but not taken forward because of unlikely adoption in China	

Option	Brief Option Description
Switching from coal (or petroleum coke) to a lower carbon fossil fuel such as oil or natural gas	Using fuel oil or gas as the kiln fuel instead of coal (or pet coke) reduces the combustion related CO_2 emissions from the clinker burning process, since these are lower carbon fuels. While implementation of this measure could be regarded as fossil fuel lock in, natural gas has the potential to be supplanted later by green hydrogen or other lower/zero carbon gaseous fuels, such as biogas. In the case of hydrogen, technical challenges would have to be overcome, such as the lower radiance of a hydrogen flame compared to hydrocarbon flames. Given the high cost of natural gas in China it is considered unattractive for adoption.
Techniques considered but not taken forward because adoption of techniques in China already expected	
Use grate coolers instead of planetary or rotary coolers	Allows for more of the heat contained in the clinker to be recovered for use in other processes. Heat recovered from clinker cooler is typically used to preheat combustion air. Additional heat recovery, facilitated by use of grate coolers, could be used to dry raw materials and, if heat still in excess, generate power.
Application of variable speed drives to motors	There are many motor applications on cement sites where significant variations in load occur. Significant examples are the motors for the induced draft fan, clinker cooler fan and exhaust kiln fan. Where VSDs are not used control is achieved using inefficient methods such as dampers, which wastes energy.
Use Vertical Roller Mills instead of ball mills to grind raw meal and clinker	Less electrical energy input is required to mill material with VRMs compared with ball mills. With VRMs, the electrical energy input is used more directly for the creation of new surface area required when materials are milled.
Use of Ground Granulated Blast Furnace Slag (GGBS) as clinker substitution	GGBS is the ground slag by-product from the production of pig iron in blast furnaces. It is an alternative cementitious material to clinker produced in a cement kiln. Its use therefore decreases the amount of clinker that must be produced for a given level of cement production. The emissions associated with the production of the displaced clinker are therefore avoided. The extent to which this clinker substitution is possible is a function of the cement's end application, where there will be specific requirements on setting time, heat generated during setting, short term strength developed, etc., which in turn are affected by the proportions of clinker and GGBS. GGBS is used in quantities ranging from 30 to 70% by mass of cement.
Use of fly ash as clinker substitution	Fly ash is obtained from the electrostatic or mechanical precipitation of dust-like particles from the flue gas of furnaces burning coal. It is an alternative cementitious material to clinker produced in a cement kiln. Its use therefore decreases the amount of clinker that must be produced for a given level of cement production. The emissions associated with the production of the displaced clinker are therefore avoided. The extent to which this clinker substitution is possible is a function of the cement's end application. The short-term strength of concrete using cements with fly ash may be decreased significantly, making it unsuitable for some applications. Fly ash is used in very different amounts in different countries of the world.

Further detail on these techniques is presented in Appendix A1.

Wet, semi-wet and semi-dry type kilns have up to 22% higher emissions intensity than dry kilns[24]. Changing kiln type requires a major rebuild or complete replacement and is therefore a major intervention. Those less efficient kiln types have been almost completely replaced in the EU with dry kilns over the past 20 years. It is understood a similar replacement programme has occurred in China and that new kilns to supply growth have been constructed as dry kilns. Therefore, very few of the less efficient kiln types remain in China meaning that kiln replacement is not considered further as a measure.

2.7 Sector Decarbonisation Issues

2.7.1 Ease of Electrification

There is currently no technically viable way of performing, at scale, the pyro-processing occurring in a cement kiln using electricity as the energy input. Moreover, the economics of doing so would, given the normally prevailing ratios of electricity and fuel prices (especially relative to coal), make this difficult to justify on economic grounds

However, developments are underway in Europe to explore the use of electrically powered plasma torches as a means of electrifying at least part of the thermal requirement of the clinker production process. Plasma torches allow for generation of the very high temperatures and very high energy transfer rates, reminiscent of fuel burner flames, necessary in a cement kiln. As such, they are considered more appropriate than other candidate electric heating processes, such as indirect resistive, induction and microwave heating.

The use of plasma torches in clinker manufacture is currently at the early demonstration stage (TRL 4) and a number of issues have to be resolved before this technology can move forward, including the short operating life of the torch, difficulty with reproducing conditions and lack of reliability of electric power sources. These make it unlikely that any meaningful part of the pyro-processing processing could be electrified within the next decade,

Given the above, measures associated with electrifying the thermal demand of cement kilns are not relevant for the time horizon considered in this project. Examples of relevant research studies are summarised in Appendix A3.

2.7.2 Ease of Switching to Lower Carbon Direct Fuels

Lower carbon fuels like biomass or waste can often be used at high substitution rates in cement kilns. However, there are limits to the extent to which this is achievable. For example, if the calorific value of the fuel is less than 22 GJ/tonne, true of most biomass and organic waste, then it will be necessary to retain some higher calorific value fossil fuel (coal or petroleum coke) for the main kiln burner to ensure that the necessary temperatures achieved in the kiln burning zone. The process temperature in the pre-calciner is lower than in the burning zone of the kiln and so higher substitution rates can be achieved in this part of the process.

In addition, although the CO_2 emissions are reduced by using lower carbon alternative fuels, the specific fuel consumption often increases owing to the relatively high moisture content necessitating drying. The thermal efficiency of the kiln will also suffer if the alternative fuel has a high chlorine content, necessitating the use of a flue gas bypass system to reduce chlorine levels and, through this, the rejection to environment of heat that would otherwise be used to preheat incoming raw meal.

The sustainable availability of these alternative fuels can also be a concern, especially in the case of biomass. Moreover, depending on wider environmental and climate change policy backdrop in the jurisdiction under consideration, there may be substantial markets for these fuels for other purposes, making it difficult to source fuel at a price that is economic for cement production.

---

[24] DEHSt, 2019, Benchmarks to determine baselines for mitigation action under the Article 6.4 mechanism (data from Cement Sustainability Initiative: Getting the Numbers Right database)

2.7.3 Process Emissions Issues

The only greenhouse gas process emissions from Portland cement clinker production is CO_2. These process emissions are significant due to the unavoidable need to calcine limestone to produce the free lime necessary for the formation of the desired clinker phases. For each tonne of clinker produced, 0.52-0.53 tonnes of CO_2 are produced from limestone calcination. For a cement plant consuming petroleum coke as the fuel and operating at a good level of thermal efficiency of ~3,300 MJ/tonne clinker, a little over 60% of total direct CO_2 emissions are process emissions[25].

Alternative cement systems which avoid the need for this calcination offer a potentially lower carbon route, but the Portland cement industry is so well established and Portland cement clinker is so well technically understood and accepted by the market that it is very difficult for these alternative systems to gain a foothold and be demonstrated as market-ready. Examples of relevant research studies are summarised in Appendix A3.

As such, the inevitable process emissions have to be managed. This can be achieved by modifying the composition of the raw meal such that the proportion of limestone in it is minimised. There is a limit to the extent to which this can be achieved while achieving the desired properties in the cement clinker and in practice the percentage reduction in process emissions that can be achieved via this route is limited. Longer term abatement of process emissions associated with limestone calcination would have to rely on Carbon Capture and Storage (CCS) or Carbon Capture and Utilisation (CCU). Capture technologies suitable for the cement sector are currently undergoing pilot scale tests (TRL 6). However, the projected costs of capture at full scale are very high at 40 to 80 €/tonne CO_2, without including any cost estimates for CO_2 transportation and storage. A number of capture technologies are possible for the cement sector, including post combustion capture using chemical or physical absorption, membranes and calcium looping. Pre-combustion capture, whereby the carbon in the fuel to be burned is sequestered before it is combusted, is less suitable for cement manufacture and has less abatement potential than post combustion capture because it does not address the process emissions. The full-scale commercial availability of CCS or CCU falls outside the timeframe of focus for this project (i.e. beyond 2030). However, to allow for consideration of longer-term planning for implementation of CCUS, further information on the status of development in Europe is provided in Section 6.

2.7.4 Investment Issues

There are many factors that influence business' decisions to invest in technologies or measures to improve energy efficiency and reduce emissions.

The ownership structure within the cement sector comprises of a relatively small number of companies with a high average number of employees per company. This increases the likelihood of companies having a dedicated environmental and/ or energy manger with an understanding of the operation, energy use, emissions and opportunities for improvement. The companies often own and operate multiple installations, often on a global level which gives access to knowledge of global best practice and technology. In addition to in-house expertise, larger companies are more likely to have better energy management systems and to be more active (or have greater potential) to assess energy use and GHG emissions.

Cement production has a relatively low value added, and low GVA per tonne of CO_2 emitted. On this basis, companies potentially are less able to pass through costs incurred from investing in decarbonisation technology into product prices as even relatively small increases can represent notable percentage change. There is therefore a greater need for investments to have short pay-back periods, with the capital cost offset by reductions in energy and CO_2 costs. Cement production installations are capital intensive, for example the cost of a new facility is equivalent to around three

---

[25] Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide

years' turnover[26]. Incremental investment such as retrofitting of equipment or changes to operating costs (raw materials, energy etc.) therefore face fewer barriers to investment.

Demand for cement is strongly correlated with demand for construction and infrastructure development and therefore linked to the overall rate of economic growth for a region or country. In periods of low economic growth, production levels are susceptible to fall, and this can lead to longer payback periods as the reduction in energy costs realised take longer to offset the investment. Under such circumstances companies are less likely to make significant investment in decarbonisation techniques[27]

A further consideration however is that the trade intensity of cement is low, with the value of imports from and exports to non-EU countries being equivalent to 7% of the value of the domestic market (domestic production + imports). Low trade intensity indicates less international competition and potentially a less price competitive market which may allow more ability to pass through costs of investment in increased product prices.

2.8 Impact on Decarbonisation from Other Sectors

Since one of the main, immediately available abatement measures is an increased use of lower carbon alternative fuels (such as biomass and waste), competition from other sectors for these same fuels will strongly influence the extent to which this option can be realised in the cement sector. In the case of waste, while cement is in a unique position in that waste fuels can come into direct contact with the product being made (and its ash is actually incorporated into the clinker product), making it more suitable for consumption as a fuel than in many other industrial sectors, there will be competition from the power sector. The extent to which this is the case will depend on the wider climate change policy environment, the extent to which power generation using waste is incentivised and the prevailing price of electricity.

In theory, the cement sector is in competition with other construction materials such as steel, ceramics (bricks, tiles), glass and timber. In practice, the actual areas of competitive overlap are small and specific. However, this could change if implementation of a particular abatement measure in the cement sector adds costs, leading to a relative deterioration in the competitive positioning of cement against its competitor materials. Similarly, economic conditions and actions taken in other construction materials sectors may indirectly influence take up of abatement in the cement sector. Furthermore, action to reduce the embodied and life-cycle emissions of buildings and other infrastructure could reduce demand for cement and therefore reduce production and emissions from the cement sector, as further described in Section 5.2.

---

[26] European Commission, Internal Market, Industry, Entrepreneurship and SMEs: Cement and Lime. https://ec.europa.eu/growth/sectors/raw-materials/industries/non-metals/cement-lime_en (accessed 05/05/2020)

[27] Ecorys etal, 2013, Carbon Leakage Evidence Project. Factsheets for selected sectors

3 Priority decarbonisation techniques

3.1 Improvement in Raw Meal Burnability

3.1.1 Technique/Technology Option Replaces

This technique involves **the addition of certain constituents (mineralisers) to the raw meal currently used in order to improve its burnability.** Improving the raw meal's burnability means facilitating the reactions that occur in the burning zone of the kiln (at 1300°C to 1450°C) which lead to the necessary formation of the calcium silicate phase alite[28] in cement clinker, which is responsible for early setting strengths in concrete.

Alite forms from the reaction of another calcium silicate phase, belite[29] and free lime and also directly from a reaction between free lime and silica. These reactions are facilitated by the formation of a liquid phase. Certain additions to the raw meal lower the temperature at which this liquid phase forms and also reduces its viscosity. This tends to ease the formation of alite and reduces the overall thermal demand for formation of the desired composition.

Fluorides are especially effective in promoting raw meal burnability and CaF_2 is generally used. CaF_2 also reduces the temperature at which calcium carbonate dissociates, leading to further fuel savings for the whole process.

3.1.2 Applicability

The extent to which this technique can be adopted **depends on the composition of the existing raw meal**. While fluorine contents of up to 1% of the raw meal achieve beneficial results, additions in excess of this can alter the composition of the clinker and can negatively affect kiln operation, for example by the formation of coatings on kiln components.

It is also necessary to weigh up the cost of these mineralisers and the value of any fuel savings arising, as mineraliser cost may not justify this on economic grounds. CaF_2 is known as highly cost intensive, but other raw materials containing fluoride are considerably cheaper and, depending on the location of the plant, may be available in good quantities.

3.1.3 Necessary Process Changes

There are **no significant process changes necessary**, but special attention will have to be paid to raw meal homogenisation, to ensure that the relatively low levels of added mineralisers are evenly distributed.

The grindability of the clinker may deteriorate and so electricity consumption for grinding may increase, although such increases are likely to be modest.

3.1.4 Impact Upon GHG Emissions/Energy Consumption

As discussed above, additions of CF_2 mineraliser reduce the temperature of calcium carbonate dissociation and the temperatures needed for the formation of the desired clinker phases. An **addition of 1% by mass of CaF_2** can reduce the clinkering temperature by 150°C with a total **reduction in fuel demand of about 180 MJ/tonne clinker (~5% decrease)**[30]. *The CO_2 savings associated with this will depend upon the fuel used.*

Modest increases in electricity consumption as a result of a deterioration in clinker grindability might **increase electricity consumption by ~1 kWh/tonne clinker (~1-2% increase)**[31].

---

[28] Alite = $3CaO.SiO_2$, also annotated as C_3S. Responsible for the development of early strength in concrete.
[29] Belite = $2CaO.SiO_2$, also annotated as C_2S. Responsible for the development of late strength in concrete.
[30] CSI/ECRA-Technology Papers 2017.Assuming kiln fuel consumption of ~3,500 MJ/tonne clinker.
[31] CSI/ECRA-Technology Papers 2017. Assuming electricity consumption of ~80 kWh/tonne clinker.

3.1.5 CAPEX and OPEX

There is usually **no significant investment** required with this measure.

OPEX savings will depend upon the relative costs of fuel and the additional electricity that might have to be consumed to grind the clinker.

As mentioned above, there may be a not insignificant additional **cost associated with sourcing the necessary mineralisers. This depends very much on the mineraliser used**, the location of the plant and the local availability of alternative fluoride containing compounds that could act as mineralisers.

3.1.6 Variables Affecting GHG and Energy Savings and CAPEX and OPEX

- The current content of mineraliser type materials in the raw meal and therefore the scope for mineraliser additions.
- The kiln fuels used and their cost
- The cost of electricity and its carbon intensity
- The local availability and cost of fluoride mineralisers.

3.1.7 Barriers and Challenges

- The cost of mineralisers, which will depend on the plant’s location.
- Negative impact on clinker quality is possible if mineraliser additions not controlled and high levels of homogenisation are not achieved.
- Clinker may become harder to grind and this will have to be accommodated within the site’s plant capabilities and scheduling.
- Negative impact on kiln operation is possible if mineraliser additions are too high, resulting in coating of kiln components, especially within the clinkering zone.

3.1.8 Interaction and Mutual Exclusivity

Absolute fuel savings from other measures may be reduced, as the baseline kiln fuel consumption will decrease.

Absolute electricity savings from other measures may increase, as the baseline energy consumption increases.

3.2 Lowering the Calcium Carbonate Content of Raw Meal (Lowering the Lime Saturation Factor)

3.2.1 Technique/Technology Option Replaces

This technique **reduces the relative proportion of the raw meal fed to the kiln which is limestone** ($CaCO_3$). Since the calcination of $CaCO_3$ is responsible for the process CO_2 emissions arising from cement clinker production, reducing the amount of $CaCO_3$ reduces the process emissions per unit of clinker produced.

Reducing the limestone content of raw meal also improves its burnability, which means that lower temperatures are necessary for the formation of clinker. This improves the thermal efficiency of the process.

The proportion of limestone in the raw meal affects the amount of lime (CaO) in the clinker. The quantity of lime in the clinker is represented by the Lime Saturation Factor (LSF), which is a ratio of the percentage by mass of lime to the other oxides found in clinker (i.e. SiO_2, $Al2O_3$ and $Fe2O_3$).

Specifically,

$$LSF = CaO / (2.8SiO_2 + 1.2Al2O_3 + 0.65Fe2O_3)$$

In Ordinary Portland Cement (OPC) manufacture, the LSF ranges from 0.92 to 1.02.

3.2.2 Applicability

The **extent to which the LSF of the raw meal can be reduced depends upon the properties sought in the cement**, which in turn depends on the application to which the cement will be put. A reduction in the LSF reduces the proportion of the clinker that is the Alite[32] phase and increases the proportion of the Belite[33] phase. This reduces the early strength development of the cement which, depending on the end application, may be problematic. Reduced early strength can be counteracted by grinding the cement to a higher fineness in order to increase the early cement reactivity, but this will obviously lead to more electricity consumption for grinding.

3.2.3 Necessary Process Changes

Depending on the early strength required of the cement, it may be necessary to increase the grinding of the clinker to produce a finer cement.

The extent to which the LSF can be reduced at a particular cement plant depends on the range of raw materials available to the site which contain the desired minerals, and the specific composition of these. Depending on the composition of the limestone used on site, reducing its proportion in the raw meal may also reduce the content of other minerals required in the clinker. This would have to be corrected by changing the proportion of other components of the raw meal or introducing altogether new components. The extent to which this would be possible and the associated cost depends on the site location.

3.2.4 Impact Upon GHG Emissions/Energy Consumption

Reducing the LSF will **reduce the process CO_2 emissions and reduce the thermal demand** on the kiln. These savings will depend on the extent to which the LSF is reduced. It is estimated that for every **0.1 point reduction in the LSF there could be decrease in fuel demand of about 120 MJ/tonne cement (~3-4%) and a reduction in CO_2 emissions of 19 $kgCO_2$/tonne cement (~3-4%)**[34].

Assuming that it would be necessary to increase the grinding of the clinker to maintain early concrete strength, there may have to be an **increase in electricity consumption of 9 to 25 kWh/tonne cement (~14%)**[34].

3.2.5 CAPEX and OPEX

There are **no special investments needed** and so there is no extra Capex associated with this measure.

There would likely be an increase in the energy costs as value of fuel savings may not offset the extra costs associated with additional consumption of electricity, but whether this is actually the case will depend on the relative costs of kiln fuel and electricity.

Any **changes in the raw material costs** resulting from this measure would be highly site specific.

3.2.6 Variables Affecting GHG and Energy Savings and CAPEX and OPEX

- The LSF currently used at the site, as this will dictate the extent to which it can be reduced.
- The actual change in LSF effected
- The relative costs of fuel and electricity
- The specific circumstances at the site regarding the range of raw materials available and the supply of these.

---

[32] Alite = $3CaO.SiO_2$, also annotated as C_3S
[33] Belite = $2CaO.SiO_2$, also annotated as C_2S
[34] CSI/ECRA-Technology Papers 2017. Assuming a thermal efficiency of 3,500 MJ/tonne clinker and a clinker : cement ratio of 0.75.

3.2.7 Barriers and Challenges

- The technical performance of concrete will be impacted unless a compensating change in the fineness of the ground clinker is achieved. However, there are limits to the extent to which the concrete strength can be fine-tuned by clinker fineness.
- Achieving market acceptability for cements which have different compositions but claim to have equivalent strength via more grinding.

3.2.8 Interaction and Mutual Exclusivity

Savings of other measures which reduce the fuel demand of the kiln are reduced in absolute terms, to the extent that the baseline fuel demand is reduced by this measure.

Measures which reduce the electricity consumption associated with clinker grinding are increased in absolute terms, as the baseline demand is increased.

3.3 Preheaters and pre-calciners

3.3.1 Technique/Technology Option Replaces

The use of cyclone preheater and pre-calciners is considered state of the art technology for the production of cement clinker.

Cyclone preheaters cause hot kiln gases passing out of the kiln to swirl and come into contact with the raw meal entering the kiln. This swirling action increases the time that these two streams are in contact with each other, bringing about an efficient exchange of heat between them. Consequently, the thermal efficiency of the process is improved.

A pre-calciner is a combustion chamber at the base of the preheater stages. Additional fuel is combusted in this chamber such that a far greater proportion of limestone is fully calcined before entering the kiln. This reduces the demand for fuel at the main burner, situated at the outlet end of the kiln, thereby improving the overall efficiency of the kiln system. For a given kiln size, the use of a pre-calciner also increases the throughput capacity of the kiln.

3.3.2 Applicability

The number of cyclone pre-heaters that can be fitted depends upon the moisture content of the raw material. Exhaust gases from the kiln are usually used to dry the raw meal as it is milled prior to feeding to the kiln. The temperature finally exhausting from the cyclone preheaters reduces as the number of cyclones increases. Where the raw meal moisture content is high and too many cyclones are used, there may not be enough residual heat to dry the feed. Therefore, where the raw material moisture content is high, the number of cyclones that can be used is lower. Indicative temperatures available in exhaust gases for raw meal drying, after passing out of cyclone preheaters, are: 6-stage about 280°C, 5-stage about 310°C, 4-stage about 350°C and 3-stage about 500°C.

In the case of pre-calciners, there are two types available: air through pre-calciners and air separate calciners. In the former case, there is no additional combustion air introduced into the pre-calciner to support combustion of fuel injected there, Consequently, the oxygen remaining in the kiln after fuel combustion at the main kiln burner has to be sufficient to support combustion in the pre-calciner. This places limits on the quantity of fuel and, therefore, extent of calcination that can take place in the pre-calciner. Additional combustion air can be introduced at the main burner; however, this would cool the flame and be counterproductive.

A higher level of calcination can be achieved in the pre-calciner if higher levels of fuel combustion are achieved via the introduction of tertiary air. This is achieved in air-separate pre-calciners where preheated combustion air is available. Such preheated air is available if grate clinker coolers are used to recover waste heat, rather than rotary coolers, and so **the choice of clinker cooler has a bearing on the type of pre-calciner that can be used.**

3.3.3 Necessary Process Changes

The economic introduction of additional cyclone pre-heaters depends upon the existing pre-heater structure (pre-heater tower) and in particular whether its height and strength can accommodate the additional cyclones. If this is not the case, the cost of implementation will be significantly higher as wider structural changes to the plant will be necessary.

The fitting of additional pre-heater cyclones should be carefully considered in the context of exiting raw meal drying operations, as **there is a trade-off between increased pre-heating and reduced raw meal drying** and it would be counterproductive to reduce kiln exhaust temperatures to levels insufficient to dry raw meal of the moisture content prevailing at the site.

Depending upon the type of cyclone used, the addition of additional stages may increase the pressure drop necessitating the implementation of larger exhaust fans, leading to additional electricity consumption. However, newer designs of cyclones are capable of achieving lower pressure drops.

In the case of the implementation of air-separate pre-calciners, the availability of preheated tertiary combustion air has to be considered. The use of grate coolers therefore facilitates the implementation of this type of pre-calciner.

3.3.4 Impact Upon GHG Emissions/Energy Consumption

The savings achievable are highly dependent on the current kiln system used. In the case of a long dry kiln without pre-heaters and pre-calciners, **the fuel demand can be reduced by about 900 MJ/tonne clinker, which represents a saving of up to 18%**[35].

Where pre-heaters are already used, the addition of additional stages can improve the thermal efficiency of the kiln system. For example, for a kiln system with 4-stage cyclone preheater system the **addition of a 5th stage could decrease fuel consumption by 80 to 90 MJ/tonne clinker, which is about 2-3%,** depending on the thermal efficiency of the existing kiln. However, as noted above, the installation of additional pre-heater stages may increase the pressure drop across them, necessitating an increase in exhaust fan electricity consumption to achieve the required range.

3.3.5 CAPEX and OPEX

Retrofit of pre-heater and pre-calciner stages to existing kilns is possible. Indicative costs provided by ECRA are **in the range €70-100 million**, although this is extremely dependent on the capacity of the kiln under consideration and local conditions.

Regarding the cost of adding additional pre-heater stages to a kiln already fitted with some, then this is heavily dependent on the ability of the existing kiln infrastructure to accept and bear the load associated with additional stages. Assuming that this is the case, then the cost would be **in the range of €5-8 million for an additional stage**. This does not include any costs associated with pre-heater tower rebuilding or the installation of larger exhaust fans to maintain acceptable levels of pressure drop, which would further increase costs.

The operating cost associated with fuel consumption would decrease in line with the fuel savings indicated above. However, depending on the type of cyclone pre-heater, the consumption of electricity may increase.

3.3.6 Variables Affecting GHG and Energy Savings and CAPEX and OPEX

The following factors have a bearing on the costs and savings associated with fitting pre-heaters and pre-calciners, and should be kept in mind:

- The initial specific fuel consumption of the kiln under consideration will determine the savings that can be achieved.
- The moisture content of the raw material will determine the number of pre-heater cyclones that can be fitted.

---

[35] Assuming a long dry kiln fuel consumption of up to about 5,000MJ/tonne clinker.

- The type of pre-heater cyclone fitted will influence the pressure drop across the kiln exhaust system and may necessitate an increase in exhaust fan electricity consumption.
- The ability of the exiting kiln infrastructure to accept additional pre-heater stages will depend its height and strength.
- The prices paid for the fuel saved and any additional electricity which may have to be consumed.
- The type of clinker cooler used determines the type of pre-calciner that can be used and, therefore, the fuel savings achievable.

3.3.7 Barriers and Challenges

The following issues could present themselves as barriers to and challenges with the implementation of this measure

- The high investment costs, which may be very high if reinforcement is required on the existing pre-heater tower, can make the payback very long and unattractive.
- The type of clinker cooler will determine the type of pre-calciner that can be used.
- The local prices of fuel, electricity and CO_2 significantly influence the payback period.
- High moisture content of raw material makes the implementation of pre-heaters less attractive if this heat is needed in the raw meal mill for drying.
- The implementation of additional pre-heaters could strand prior investments in heat recovery for the generation of electricity, as less waste heat energy will be available for conversion to electricity.

3.3.8 Interaction and Mutual Exclusivity

The implementation of additional pre-heaters and pre-calciners may impact other aspects of kiln operations. Some salient examples are:

- In some cases, more electricity may have to be consumed in exhaust fans if the required levels of pressure drop are to be maintained.
- The implementation of pre-calciners facilitate the consumption of more waste as a fuel, as a greater quantity of these lower calorific value fuels can be tolerated in the pre-calciner than can be tolerated at the main kiln burner.
- The potential for recovery of heat from the kiln exhaust for the generation of electricity is reduced, as more thermal energy is used up pre-heating the raw meal feed to the kiln.

3.4 Use of Alternative Fuels (with biogenic content) in Cement Kiln

3.4.1 Technique/Technology Option Replaces

This option replaces the incumbent fuels used for generating heat within the clinker kiln and, where they are currently part of the kiln system, pre-calciners.

The incumbent fuels will be, in the main, fossil fuels such as coal, petroleum coke, oil of natural gas, which can be substituted with biomass or wate derived fuels with lower carbon intensity. In the case of clinker production in China this will be coal, where over 90% of fuel input to clinker production is coal.

3.4.2 Applicability

This option is available to **all cement kilns producing Portland Cement Clinker** (PCC). The chemistry of the PCC production process is very tolerant to the use of waste or biomass fuels, as the very high temperature of clinker burning (1450°C) destroys any harmful halogenated organic substances which may reside in these alternative fuels. Moreover, the ash from the combustion of waste and biomass may be readily incorporated in the clinker. As such, the use of waste and biomass may reduce the quantity and, therefore, costs of raw meal fed to the kiln. This has the added benefit of reducing the process CO_2 emissions associated with limestone calcination, as less limestone containing raw meal needs to be fed to the kiln for tonne of clinker produced.

Before a waste stream can be considered as a substitute fuel a number of considerations have to be made. These include:

- Determining whether the composition of the biomass or waste's ash products is compatible with the desired chemical properties of the final clinker product
- Whether the kiln's flue gas cleaning system is able to deal with the combustion products from the combustion of biomass or waste
- The calorific value of the substitute fuel
- The consistency of substitute fuel composition and calorific value over very large volumes of substitute fuel.

In the EU, a wide variety of waste fuels have been used. These include:

- Grade A waste wood chip
- Solid Recovered Fuel (SRF)
- Tyres (in so far as the tyre has a proportion of natural rubber)
- Sewage sludge
- Meat and bone meal
- Wood paper and cardboard, textiles, plastics

Waste and biomass fuels may be retrofitted to existing kilns. A wide range of substitution levels has been demonstrated in cement kilns in Europe and **substitution rates of up to 80% have been achieved with waste fuels**.

The **availability of biomass and waste as a fuel is strongly influenced by the environmental policy** in the jurisdiction under consideration. For example, bans on and penalties associated with landfilling unprocessed wastes in some EU countries can make waste available as a fuel at low or negative cost. On the other hand, policies incentivising the generation of electricity using biomass or waste, or the generation of heat using biomass, can lead to a diversion of substitute fuels to these applications, as operators of these plant may be willing to pay a higher price for the fuel than would be economic for a cement kiln operator. Therefore, while there may be significant technical potential for the use of waste and biomass, the aggregate effect of environmental policy may place economic limits on the level of substitution that is possible. This means that wider environmental policy in China needs to be factored in when considering policy levers that could increase the use of waste and biomass fuels in cent kilns.

3.4.3 Necessary Process Changes

While high levels of waste substitution have been achieved at some EU sites, the **level of substitution possible is a function of the waste and biomass calorific value**. Generally speaking, the fuel fed to the main burner at the outlet end of the cement kiln needs to have a calorific value not less than 20 to 22 GJ/tonne in order for the required clinkering temperatures to be developed. However, many organic materials have calorific values in the range 10 to 18 GJ/tonne, while some waste fuels such as plastics, waste solvents and oily waste tend to consistently have calorific values >20 GJ/tonne. This fact places something of a limit on the level of substitution that is possible for the main burner fuel. In contrast to this, kiln systems with pre-calciners, which require much lower process temperatures, are able to accept a higher proportion of low calorific value fuels than at the main burner. The fact that the pre-calciner takes the majority of the thermal input to the kiln means that high levels of organic fuel substitution can be achieved with kilns with pre-calciners.

Waste and biomass fuels are prone to having trace elements of chlorine. Fuels with high concentrations of chlorine can suffer from coating in a number of places in the kiln inlet system and from the development of rings in the rotary kiln, which must be avoided or removed. If removed, then then kiln production has to be suspended for a period of time, resulting in reduced productivity of the kiln and an increase in specific energy consumption. The build-up of these deposits can be avoided by the use of a chlorine bypass system. In such systems, some of the kiln exhaust is bled and cooled to allow the chlorine species to condense out, thereby reducing the concentration of chlorine in the exhaust gas passing through the kiln inlet. However, this leads to a deterioration of thermal efficiency of the kiln as exhaust heat which would have been used to preheat raw meal is dumped to atmosphere.

A barrier to uptake of waste derived fuels and biomass which has been identified by cement companies in certain countries is the lack of **reliable, steady availability of that fuel type.** This requires a fuel supply chain and market, with companies that prepare fuels from waste and/or biomass feedstocks with consistent calorific value and composition. Furthermore, this can also be hindered where there is a lack of sufficient capacity within companies or third part laboratories for the testing and certification of fuel composition and quality.

3.4.4 Impact Upon GHG Emissions/Energy Consumption

The specific CO_2 emissions savings per unit mass of clinker produced will be driven by the CO_2 intensity of the fuel it is replacing, the biogenic content of the waste fuel and the CO_2 intensity of the waste fuel's non-biogenic content.

It is very common outside of regions where natural gas and oil are very cheap for the main fossil fuel used to be coal and/or petroleum coke. As such, the CO_2 intensity of the incumbent fuel is usually very high (Coal: 0.331 tCO_2/MWh, Pet. Coke: 0.342 tCO_2/MWh[36]). This can be contrasted with the emission factor for Solid Recovered Fuel (SRF)[37], a fuel used commonly in UK cement kilns of 0.145 tCO_2/MWh[38], where approximately 60% of the fuel is biogenic.

While there are very significant CO_2 savings to be made by substituting incumbent fossil fuels with biomass and or waste, the energy consumption may actually increase. There are two main reasons for this:

- Waste and biomass fuels usually have higher moisture contents than the incumbent fuels of coal and petroleum coke. This means that, at higher levels of substitution, new draught fans may be need, leading to increased electricity consumptions (as well as increased capital cost).
- Biomass and waste fuels often have higher chlorine contents than incumbent fuels, necessitating the use of kiln exhaust gas systems to avoid the build-up of deposits and, consequently, a reduction of the transfer of heat to incoming raw meal and lower levels of efficiency.

The European Cement Research Academy (ECRA) estimates that **substitution rates of up to 65% can lead to an increase in fuel energy consumption of 200 to 300 MJ/tonne clinker** (against a baseline of ~3,500 MJ/tonne clinker) and **electricity increases of 2 to 4 kWh/tonne clinker** (against a baseline of about 70 kWh/tonne clinker[39]).

In the hypothetical case of a kiln consuming only coal and operating at a thermal efficiency of 3,500 MJ/tonne clinker, attaining a substitution rate of 65% SRF would reduce total direct emissions from clinker burning from about 884 $kgCO_2$/tonne clinker to 765 $kgCO_2$/tonne clinker, or 14%. This represents a reduction in combustion emissions of 33%. Under this option the process emissions remain the same (~520 $kgCO_2$/tonne clinker) and are about 60% and 70%, respectively, in the two cases. This highlights the need for addressing the process emissions if significant in-roads are to be made with reducing the CO_2 emissions associated with clinker production.

3.4.5 CAPEX and OPEX

The CAPEX which must be observed relates to biomass and waste fuel processing, storage and handling facilities and changes made to the kiln's exhaust systems, including draught fans. The ECRA

---

[36] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019

[37] Solid Recovered Fuel (SRF) is a fuel produced by shredding and dehydrating solid waste via a process such as Mechanical and Biological Treatment (MBT). SRF is different from Refuse Derived Fuel (RDF) in that it is produced to fall within tighter bands of composition and calorific value.

[38] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/372992/RHI_Evidence_Report_-_Direct_Applications_of_Renewable_Heat.pdf

[39] CSI/ECRA-Technology Papers 2017. This is baseline electricity consumption for a reference cement plant and includes only electricity consumption associated with the kiln operation and excludes electricity for subsequent clinker grinding.

places these **costs in the region of €5 to 15 million** for a reference kiln of 2 million tonnes clinker per year capacity.

Operational costs will be driven by the relative costs of the coal/petroleum coke displaced and the alternative fuel. As mentioned, the price at which a cement site might be able to secure waste will depend on whether there is demand for this waste for other applications, such as power generation and the price that these other users would be prepared to pay. As such, operational costs will be highly location specific. It is also necessary to take into consideration a likely increase in the consumption of electricity by the kiln (for the reasons discussed above) and the effect of this, again, will depend upon the local price of electricity, which will also be location specific.

3.4.6 Variables Affecting GHG and Energy Savings and CAPEX and OPEX

- Availability of alternative fuels – Extent to which other users of alternative fuels want the fuels and the price they are prepared to pay.
- Composition of alternative fuels - In the case of waste fuels, the biogenic content of the available waste will determine the CO_2 savings that might be achieved. In the case of biomass and waste, the composition will also determine whether additional flue gas treatment or flue gas by-pass systems are needed.
- Moisture content of the biomass/waste – This will affect the volume of gasses which must be exhausted from the kiln, with high levels of moisture appreciably adding to this. It may therefore be necessary to change the draught fans (with a CAPEX implication) and larger fans having to move a greater volume of gasses would increase electricity consumption. High moisture content alternative fuel will also require thermal energy for drying.

3.4.7 Barriers and Challenges

- Availability of waste and biomass – Depending on the overall environmental policy background, demand for these fuels by other end users can affect availability for use in cement kilns.
- Availability of technical expertise to operate cement kiln running at high levels of fuel substitution.
- Fact that use of alternative fuels may reduce the capacity of the cement kiln, may limit the lifetime of kiln refractory and lead to blockages, in the case of high chlorine content fuels
- The need to, and difficulties associated with, getting a permit from the local competent authority to burn waste fuels
- Available capacity for testing and certification of fuel quality
- Acceptance of the local public for the burning of waste fuels
- Higher investment costs to cover plant to process the alternative fuel

3.4.8 Interaction and Mutual Exclusivity

As discussed above the consumption of biomass and waste fuels are likely to increase both the specific fuel and electricity consumption of the kiln system. Therefore, other energy efficiency options that inherently reduce fuel and electricity consumption would have a greater impact on kilns using high levels of alternative fuels.

3.5 Recovery of Heat from Kiln and Clinker Cooler

3.5.1 Technique/Technology Option Replaces

This technology applies to cement sites where **waste heat from the kiln and clinker cooler**, still available after best practice measures are implemented, is recovered and utilised. Best practice measures for the utilisation of waste heat are:

- Heat in kiln gases leaving the preheater stage is used to dry material inputs to the process, such as raw meal, alternative fuels and alternative materials added to clinker for cement production, such as slag.
- Heat from the clinker cooler is used to preheat combustion air for the kiln burners.

If, after these processes, there is still **heat of an acceptable grade** available, this **can be used to generate power.** If there is a demand for it in the vicinity of the cement site, steam or hot water can also be generated – after raw material and fuel drying needs have been satisfied, it is unlikely that there will be a further need for this heat on site, owing to its relatively low grade.

3.5.2 Applicability

The **availability of surplus heat from these sources is strongly site specific**. Sites utilising high moisture content raw materials and fuels will utilise more heat for drying than other sites and, consequently, heat at a lower temperature will be available for other purposes. This fact will affect the choice of heat recovery technology and, therefore, the economics of recovery projects. In addition, the availability of heat from the clinker cooler for purposes other than preheating combustion air depends upon the type of clinker cooler in operation. Only heat from grate coolers is available for purposes other than preheating combustion air. This means that waste heat from clinker for a purpose other than combustion air preheating is not applicable at sites still using rotary coolers.

In cases where power generation is being considered, the temperature at which waste heat is available will be a strong determining factor of the technology used.

Currently, three technologies are used at cement sites to generate power using waste heat. These are:

Steam Rankine Cycle (SRC)– Water steam is generated in a waste heat boiler and is then passed through a steam turbine. The temperature at which waste heat is likely to be available at a cement plant (200-400°C) means that the efficiency of generation by this technology will be significantly lower than the efficiencies achieved in commercial power plants operating the SRC. As such, it may be appropriate to consider some of the other power generation options available (see below). It is understood that the SRC is used widely in China for power generation using waste heat at cement sites and has become a way of overcoming issues related to the supply of power to industrial sites in China.

Organic Rankine Cycle (ORC) – This uses an organic fluid as the working fluid, such as n-pentane or toluene. The lower boiling temperature of this fluid means that it can effectively recover heat for power generation from lower temperature sources (150 - 350°C) and can therefore access waste heat temperatures at which the SRC would be very inefficient. Nevertheless, the efficiency of ORC power generation is quite low in itself, with efficiencies in the range 10 – 20%, depending on the temperature of waste heat available. This technology has been implemented at cement sites in several countries, although the prevalence of this in China is not clear.

Kalina Cycle (KC)- This is a variant of the other Rankine cycle technologies but instead uses a working fluid with two components of different boiling points. The most common mixture is water and ammonia. Using a working fluid of two components means that the average temperature over which heat is absorbed is increased and the average temperature over which heat is removed during the condensing cycle is decreased, resulting in an increase in the efficiency of power generation. Judicious use of different working fluids and their relative proportions means that heat can be recovered from lower temperatures and power generated at higher efficiency than would be possible with a Rankine cycle (SRC or ORC) using a single component working fluid. This technology has already been implemented in Pakistan and United Arab Emirates.

3.5.3 Necessary Process Changes

Waste heat boilers have to be installed to recover heat from the clinker cooler and/or the exhaust gas from raw meal preheating. The placement and choice of these waste heat boilers and auxiliary systems has to be carefully considered so as to avoid the build-up of dust on heat exchange surfaces which cannot be economically removed. Depending on site configurations, the WHB may need to be installed after electrostatic precipitators or bag filters.

In the case of ORC, for safety reasons, it is usually necessary for exchange of heat to be a two-stage process, with one stage exchanging heat between clinker cooler/kiln heat and a thermal oil circuit and the latter then exchanging heat with the organic working fluid.

3.5.4 Impact Upon GHG Emissions/Energy Consumption

In these cases, additional electricity consumption for pumping of fluids will be necessary to support the operation of the WHB and the turbine and so the absolute electricity consumption associated with cement production on the site will increase. However, there will be an absolute fall in power imported from elsewhere and an **absolute fall in CO_2 emissions associated with electricity consumption.**

The CO_2 emissions saved will be determined by the CO_2 intensity of the electricity that is being displaced by the on-site generation from recovered heat.

The quantity of electricity that may be generated by the recovered waste heat will strongly depend on the temperature of heat available which, as discussed above, is a function of the amount of drying of raw materials and fuel that is necessary. Generally speaking, the lower the temperature of waste heat available after drying needs are met the lower will be the efficiency of electricity generation, however the trade-off between temperature and generation efficiency can be mitigated by moving away from the Steam Rankine Cycle towards the Kalina Cycle.

Nevertheless, the following ranges of power generation may be considered for the candidate technologies:

Steam Rankine Cycle[40]

Clinker cooler -8 to 10 kWh/tonne clinker

Kiln gases – 9 to 12 kWh/tonne clinker

Organic Rankine Cycle[40]

Clinker cooler and kiln gases -10 to 20 kWh/tonne clinker

Kalina Cycle[40]

Clinker cooler and kiln gases -10 to 22 kWh/tonne clinker

3.5.5 CAPEX and OPEX

The Capex for the implementation of the three heat recovery opportunities for the generation of power will vary significantly from site to site. Therefore, a site-specific appraisal would have to be carried out and include quotes from the companies specialising in implementing these solutions.

However, according to the ECRA, for a typical plant operating the dry process producing 2 million tonnes of clinker per year, Capex for the implementation of these measures would be in the range of **€15 to 25 million**.

There would be an operational cost saving which would depend on the price paid for the electricity displaced by these measures. Operational cost increases associated with the operation and maintenance of the new plant would be highly dependent on whether the cement site decides to operate and maintain the new plant or contract this out to a 3rd party and, in the case of the second, the terms of agreement with the 3rd party.

3.5.6 Variables Affecting GHG and Energy Savings and CAPEX and OPEX

- The temperature at which waste heat is available after on-site demands of raw material and fuel drying have been satisfied.
- The CO_2 intensity of electricity displaced by the electricity generated from waste heat recovery.
- Specific physical on-site constraints introducing complexity to implementation of the option, for example, positioning of HRBs to avoid the worst effects of dust formation on heat transfer surfaces.
- Arrangement made with 3rd parties regarding the operation and maintenance of the heat recovery and power generation plant.

---

[40] CSI/ECRA-Technology Papers 2017

3.5.7 Barriers and Challenges

- The availability of heat at a temperature at which the efficiency of power generation is high enough to justify the capital expenditure.
- The price paid for electricity displaced is high enough to justify the capital expenditure.
- The type of clinker cooler used, with heat recovery for uses other and preheating combustion air only being possible if grate clinker coolers are used.
- The size of kiln operations, quantity of waste heat available and, therefore, electricity generated not being large enough to justify the capital expenditure.

3.5.8 Interaction and Mutual Exclusivity

Options to increase the efficiency of kiln operations by reducing the quantity of heat wasted will reduce the quantity of electricity that can be generated. As such, kiln efficiency measures, with regards to waste heat generated, and use of waste heat for raw materials and fuel drying, should be implemented first before considering recovery of waste heat for other proposes, and such options will often have shorter paybacks.

There will be an increase in absolute electricity consumption, but a decrease in supply of electricity from other sources.

3.6 Summary of priority techniques

A summary of the potential impacts of each technique on energy consumption and process emissions, and of the associated costs, are presented in the following table.

Table 2 Summary of priority techniques

Option	Scale of Abatement Thermal (fuel)	Scale of Abatement Electrical	Scale of Investment
Improvement in Raw Meal Burnability **(e.g. for addition of 1% CaF_2)**	Decrease of 180 MJ/tonne clinker ~5% decrease	Increase of 1 kWh/tonne clinker (reduced grindability) ~1% increase	None, but there will be additional operational costs for sourcing the mineraliser material.
Lowering the Calcium Carbonate Content of Raw Meal **(e.g. for lowering the Lime Saturation Factor by 0.1 point)**	Decrease of 119 to 125 MJ/tonne cement ~3-4% decrease	Increase of 9 to 25 kWh/tonne cement, depending on additional grinding that is undertaken to offset the lower initial strength of concrete. ~14% increase	None
	Reduction in process emissions: 19 $kgCO_2$/tonne cement ~3-4% decrease		
Adopt preheaters and pre-calciners	Decrease of up to 900 MJ/tonne clinker, depending on the number of stages added. ~18% decrease	Possible increase in exhaust fans if required to offset pressure drop.	Up to €70-100 million per kiln, depending on kiln capacity and number of stages added.

Option	Scale of Abatement Thermal (fuel)	Scale of Abatement Electrical	Scale of Investment
Use of Alternative Fuels (with biogenic content) in Cement Kiln	Increase of 200-300 MJ/tonne clinker. ~7% increase Decrease of ~120 kg CO_2/tonne clinker - ~33% decrease Values are highly dependent on the level of substitution and the fuel mix before and after the change.	Increase of 2-4 kWh/tonne due to higher exhaust fan consumptions needed to move a greater mass of combustion products. ~3% increase	€5-15 million, for clinker capacity of 2 million tonnes p.a.
Recovery of Heat from Kiln and Clinker Cooler	N/A	Decrease of 5 to 22 kWh/tonne clinker ~11% decrease	€15-25 million, for clinker capacity of 2 million tonnes p.a.

If all five measures are adopted simultaneously the cumulative impact will be less than the total of the individual impacts, due to the interactions of measures adopted in combination.

- Up to 20% decrease in thermal energy demand would be achievable, with a corresponding reduction in combustion CO_2 emissions. However, if fossil fuels are replaced by biomass then the CO_2 benefits of reducing fuel consumption via energy efficiency measures are reduced.
- The reduction in combustion CO_2 achieved by fuel switching depends on the fuel mixes before and after and the level substitution. A 33-50% reduction in emissions is achievable, with 80% reduction potentially being possible with higher substitution subject to availability of suitable biogenic fuels.
- There would be an overall increase in electricity demand in the order of 7%. As the indirect emissions from electricity consumption are a small part of the overall CO_2 intensity of production, this increase will only counteract the benefits of reducing the direct emissions by 1-2% (depending on the emission factor of the electricity used).
- Up to 4% reduction in process emissions would be achieved.

The overall effect would be a reduction on emissions intensity of clinker production in the order of 20%.

Table 3 Illustrative example of emissions reduction potential

Emissions	Contribution to intensity before application of measures	Reduction	Contribution to intensity after reduction
Process emissions (direct)	0.52 tCO_2/t clinker	4%	0.50 tCO_2/t clinker
Combustion emissions (direct)	0.52 tCO_2/t clinker (assuming coal fuel, dry kiln of average efficiency without pre-heater or pre-calciner)	33% reduction in fuel emission factor (65% switching to mixed waste derived fuels). 20% reduction in energy demand. = 46% reduction in emissions	0.28 tCO_2/t clinker
Electricity emissions (indirect)	0.13 tCO_2/t clinker	7% **increase**	0.14 tCO_2/t clinker
Total	1.17 tCO_2/t clinker		0.92 tCO_2/t clinker

4 High level assessment of reduction potential in China

China is the biggest producer of cement globally, accounting for more production than all other countries combined. The U.S. Geological Survey[41] shows production of cement in China in 2018 accounts for 2.2 billion tonnes of the global total of 4.1 billion tonnes (i.e. circa 54%).

In 2018, China's cement industry CO_2 emissions from energy consumption were 752 million tonnes and cement output was 2.18 billion tonnes[42]. Analysis of data presented in the same report indicates an average intensity of 0.346 tCO_2 / t cement from energy consumption. It is not specified whether this is only direct combustion emissions or if this also includes electricity related indirect emissions. There is 7% variation between provinces, ranging from 0.339 tCO_2 / t cement (in Jiangsu, Anhui, Zhejiang, Fujian and Shanghai) to 0.365 tCO_2 / t cement (Liaoning, Heilongjiang and Jilin).

This same report[42] also indicates process emissions are about 0.33 tCO_2 / tonne cement, which results in an overall average intensity of 0.676 tCO_2 / tonne cement with 51% attributed to energy emissions and 49% to process emissions. As process emissions account for 0.51 tCO_2 / tonne clinker, this implies an average clinker content in cement of 65%, which is consistent with IEA[43] reporting of 64% clinker to cement ratio in 2018. On this basis, the average overall intensity for clinker production can be derived to be 1.04 t CO_2 / t clinker.

However, a review of other available studies identified lower values. A value of 0.79 t CO_2 / t clinker for 2016 could be derived from data contained in one study[44]; based on 1,295 Mt clinker produced and 1,019 Mt CO_2 emissions, with approximate apportionment of 13% combustion, 24% electricity, 63% process. This is consistent with analysis of data from China Statistical Yearbook 2019. Another study[45] calculated an estimate of 0.883 t CO_2 / t clinker for 2013, with a breakdown of emissions of 36% combustion, 5% electricity and 59% process. However, it is improbable that combustion emissions can be so low in China while fossil fuels account for ~90% of fuel consumption[46] even though several studies identify Chinese cement kilns as being more modern and energy efficiency than kilns in Europe which are older on average.

The variation in between the above estimates of intensity for clinker production may be due to inconsistencies in coverage of the various data sets used, for example differences in accounting for indirect emissions, gaps in data for certain producers and differences in assumptions made. The uncertainty in determining the current emissions intensity of clinker production in China means a detailed quantitative estimate of the emissions reduction potential in China of adopting of the measures described in Section 3 would be similarly uncertain.

Instead, a simplistic top-down indication of the annual emissions reduction potential is provided in the following table, on the basis of 100% uptake of the measures. This estimates an indicative reduction of 239 Mt CO_2, equivalent to 16% of total emissions from cement production, could be avoided.

---

[41] U.S. Geological Survey, Mineral Commodity Summaries, 2020

[42] Green World Low-carbon Economy & Technology Center , 2020, Analysis of Energy Consumption and Carbon Emissions of Main Industries sector in China

[43] IEA, 2020, Cement. https://www.iea.org/reports/cement

[44] Shan, Y., Zhou, Y., Meng, J., Liu, J., Guan, D., 2019, Peak cement-related CO2 emissions and the changes in drivers in China

[45] Yang, Y., Wang, L., Cao, Z. et al. (2017) CO2 emissions from cement industry in China: A bottom-up estimation from factory to regional and national levels. J. Geogr. Sci. 27, 711–730. https://doi.org/10.1007/s11442-017-1402-8,

[46] For comparison, weighted average direct (excluding electricity) emissions intensity of European clinker production in 2018 was 0.815 tCO2 / t clinker (ranging from 0.61 to 0.90 tCO2 / t clinker between installations). This corresponds with a fuel mix of 52% fossil fuels, 31% mixed wastes and 17% biomass. Global Cement and Concrete Association (GCCA), 2020, Getting the numbers right (GNR) reporting, https://gccassociation.org/gnr/

Table 4 Indication of emissions reduction potential in China

Emissions	China total	Reduction	Emissions avoided
Process emissions (direct)	2.18 bn tonnes cement x 0.33 tCO_2 / tonne cement = 719 Mt CO_2	4%	29 $MtCO_2$
Combustion emissions (direct)	752 Mt x 66% (assuming* total energy related emissions reported above includes electricity related emissions, and that combustion emissions account for 66% of total energy emissions)	33% reduction in fuel emission factor (65% switching to mixed waste derived fuels). 20% reduction in energy demand. = 46% reduction in emissions	228 $MtCO_2$
Electricity emissions (indirect)	752 Mt x 34% (assuming* electricity emissions account for 34% of total energy emissions)	7% **increase**	18 $MtCO_2$ increase
Total	1,471 Mt CO_2	16%	239 Mt CO_2

* Based on an assumed split in contribution of energy emissions between direct combustion and indirect electricity that is the average of that identified in available studies[44,45].

In practice, 100% additional uptake is unfeasible. Low levels of uptake of the measures has already occurred in China[42] and there will be other instances in which there are technical barriers which prevent their take up. So, a maximum take-up of 80-90% may be possible, resulting in 14% reduction of total emissions from the sector. This level of uptake would still require significant investment and therefore need political intervention to make it happen.

5 Circular economy considerations

The measures identified in Section 0 focus on actions which can be taken within the cement industry to reduce emissions intensity of cement production. Overall emissions from the sector would also be reduced if production of cement decreased. This section explores opportunities to reduce demand for clinker production. It is recognised that average building lifetime is low in China[42] so there is significant opportunity to draw on European experience and on-going developments for minimising clinker demand.

The ‘circular economy’ paradigm is based on the principles of designing out waste and pollution (‘reduce’), keeping products and materials in use (‘reuse’), and balancing resource flows between finite and renewable sources in order to preserve natural capital (‘recycle’), whereby the value of the recycled materials can be conserved[47]. These principles are being applied in the European cement sector through a range of measures across the production of cement as well as in relation to the use of cement and concrete products, with the aim to reduce GHG emissions overall.

---

[47] Ellen McArthur foundation. See: https://www.ellenmacarthurfoundation.org

5.1 Production

5.1.1 Substitute fuels and raw materials

Circular economy measures that have already been widely adopted in the EU's cement sector over the past few decades include the use of waste fuels and clinker substitution, as described earlier. These make use of materials that would otherwise be considered wastes.

To recap, lower carbon substitute fuels such as waste or biomass are being used in cement kilns instead of coal (or pet coke) as these reduce combustion related CO_2 emissions from the clinker burning process, although the extent of substitution is limited for different technical reasons. The types of substitute fuel used in the EU include secondary liquid fuel such as recovered fuel oil (RFO), whole or chipped tyres (which have the same calorific value as coal), solid recovered fuels such as refuse-derived fuel (RDF), biofuels such as meat and bone meal (MBM) and processed sewage pellets (PSP), and secondary liquid fuel (recovered solvents). In 2016, biomass accounted for 15% and non-biogenic or mixed wastes for 30% of fuel use in EU cement production[48].

The ashes from these waste fuels form part of the clinker and certain waste types have favourable properties allowing for reduction in use of raw materials. Small quantities of non-combustible wastes containing calcium, silica, alumina and iron are also used to reduce consumption of primary raw materials (clay, shale and limestone). Such use of wastes in clinker production has offset the use of raw materials by 3-4%, equivalent to 14.5 million tonnes per year, which reduces resource demand and emissions from quarrying and potentially from the transportation, preparation and process emissions[49].

Higher up the circular economy value chain there is clinker substitution, whereby secondary cementitious materials such as fly ash and gypsum (waste products from exhaust cleaning systems in coal fired power stations), ground granulated blast furnace slag (GGBS) (a waste product from iron production), limestone fines (by-product of quarrying and crushing) and silica fume (a waste product from silicon production for electronics), are substituted for cement clinker. This reduces the overall amount of clinker produced by burning primary raw material such as quarried limestone in the cement kiln. The emissions associated with the production of the displaced clinker are thus avoided and reduced overall. In line with circular economy principles, materials that might otherwise be landfilled are reused and the amount of raw materials consumed is reduced.

Admixtures[50] may also be sourced as by-products from other industries, for example, chemicals and wood residues from pulping in the paper sector which would otherwise be classed as waste[49].

5.1.2 Industrial symbiosis

In adopting such measures, the cement sector is not acting in isolation but as a part of a wider network for the supply of substitute materials, with inter-company partnerships across different industry sectors and predominantly at the local and national levels. Such a cross-sector approach is important, as further circular economy measures in the cement sector are likely to require greater industrial symbiosis with other industry sectors. In particular for construction, to return concrete back into the production cycle and to reduce the input of primary raw materials. Such further measures will need to be cost-effective and provide incentives for the industry.

There may also be opportunity for recovered waste heat to be transferred for use in neighbouring industries or district heating networks. Such opportunities can be limited as clinker production is normally sited close to the source of raw materials which may be in relatively remote areas. In which case recovered heat can be used to generate electricity for on-site use and any surplus could be supplied to the grid.

---

[48] ECRA refence document.
[49] CEMBUREAU, Raw Material Substitution. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/raw-material-substitution/
[50] Admixtures are small quantities (<2%) of chemicals added during the mixing of the concrete to modify its properties once hardened.

5.2 Use

A further solution for reducing emissions from the production of cement is to reduce overall demand for cement by developing buildings designed for longer useable life. This can be achieved via higher quality concretes and efficiency of use. Material efficiency is one of the most effective means to reduce emissions from construction. This means avoiding excess material use without compromising the size or structural integrity of the building. Requiring high durability of the construction materials, in this case cement used in concrete, also allows for longevity of buildings. This reduces the rate of replacement and therefore reduces demand for the production of cement.

Premature dismantling of structures is detrimental to the environment, due to the discharge of used materials to landfills and the need for the manufacture of new ones. The longer the period of time in which the building is used, the lower is its annual share of embodied energy used for construction[51]. Therefore, it is more carbon efficient to create a building with long-lived components and adapt an existing building than for it to be dismantled and reconstructed.

Furthermore, optimising the building design and procurement of high-quality building materials can allow for minimising of over-engineering and excess use of materials. It can also facilitate the re-use of modular standardised components. Assuming they retain their integrity, which is more likely with high durability cement, these standardised components may be removed during deconstruction and reused in the construction of another building.

5.2.1 Material quality and durability

Cement is mixed with aggregates (sand or gravel), water and air to form concrete. Including “admixtures” can improve the quality and durability of the concrete. Admixtures are small quantities (<2%) of chemicals added during the mixing of the concrete to modify its properties once hardened. This can reduce the permeability of the concrete and improve resilience to environmental conditions (temperature fluctuation, salt water). In Europe, approximately 80% of ready-mixed and precast concrete includes admixture[52].

Material quality of cement and concrete is assured through standards for parameters affecting the composition and property.

Cement standardisation

The European Committee for Standardization (CEN) is working to harmonise building materials across the EU with the aim of supporting Construction Products Regulation (CPR) ((EU) No 305/2011). The regulation seeks to provide construction products, such as cement, with European Certification (CE). Cement marketed in the EU requires the CE to prove it meets minimum/maximum levels of performance for mandated essential characteristics, such as minimum limits to early-age strength and for 28-day strength. A Declaration of Performance is provided for every product of cement and comprises detailed information about the product plus a list of its essential characteristics against which performance has to be declared by level, class or in a description[53].

---

[51] Celadyn, W,, 2014, Durability of buildings and sustainable architecture

[52] CEMBUREAU, Low carbon concrete https://lowcarboneconomy.cembureau.eu/5-parallel-routes/product-efficiency/low-carbon-concrete/

[53] https://cement.mineralproducts.org/documents/FS_9_CE_marking_declarations_performance_cements.pdf

CEN/TC 51 is the technical body governing the harmonisation of cement and building limes for Europe. European standards for cement are based on British standards:

- BS EN 197-1:2011 Cement. Composition, specifications and conformity criteria for common cements
- BS EN 197-2:2020 Cement. Assessment and verification of constancy of performance
- BS EN 14216:2015 Cement. Composition, specifications and conformity criteria for very low heat special cements
- BS EN 14647:2005 Calcium aluminate cement. Composition, specifications and conformity criteria
- BS EN 413-1:2011 Masonry cement. Composition, specifications and conformity criteria
- BS EN 15743 Supersulfated cement - Composition, specifications and conformity criteria

BS EN 197-1 defines 27 distinct common cement products and their constituents. These 27 products are grouped into the following categories[54]:

- CEM I Portland cement (>95% clinker)
- CEM II Portland-composite cement (65-94% clinker)
- CEM III Blast furnace cement (5-64% clinker)
- CEM IV Pozzolanic cement (45-89% clinker)
- CEM V Composite cement (20-64% clinker)

Studies investigating engineering (compressive cube and cylinder compressive strength, flexural strength, drying shrinkage) and durability properties (initial surface absorption, carbonation) of BS EN 197-1 cements found that cements produced to this standard demonstrate improved results compared to conventional Portland cement concrete mixes that are otherwise designed for equal strength[55].

Concrete standards

The quantity of cement used in concrete can be a factor affecting durability. Too little cement reduces workability whereas too much can cause durability issues such as drying shrinkage.

The quantity and quality of water added to a concrete mix can also impact durability. Too much water can form capillary voids which cause concrete to become a more permeable material. The water needs to be good quality with a central pH rating and free from oils, salts, sugars and organic materials that could lead to corrosion of steel or the deterioration of the concrete.

Use of good quality aggregates in concrete mix will increase the durability of hardened concrete. Aggregates should be well graded to achieve a dense concrete mix. Smooth and round particles can optimise workability whereas flaky and elongated particles can promote better bond developments at the expense of more cement use.

To enhance durability, concrete should be tailored to the local climate and environment. Humid and wet environments should have lowest possible water cement ratio possible to reduce permeability and protect from water intrusion. Unwanted water can expand with heat, causing cracks in the concrete. Freezing and thawing can have similar effects at a faster rate, durability can be achieved by adding air-entraining admixtures and reducing the maximum size of course aggregate. Interaction with sulphates in soils can damage concrete without sulphate resistant cement. Similarly, salt from marine environment or de-icing salt can cause corrosion of concrete and the reinforcement steel contained in the concrete[56].

---

[54] https://www.cemex.co.uk/documents/45807659/45840198/mortar-cementitious.pdf/46571b2a-3efd-4743-20c8-d33feb1aed9d

[55] https://www.sciencedirect.com/science/article/abs/pii/S0950061814009738

[56] Concrete has high compressive strength but low tensile strength. Concrete is therefore commonly cast around reinforcing steel rods to provide the tensile strength to the composite structure.

There are also European standards to promote consistency in quality of concrete for different applications. For example, European concrete standard EN 206-1 Concrete – Part 1: “Specification, performance, production and conformity” applies to concrete for structures cast in situ, precast structures, and precast structural products for buildings and civil engineering construction. Concrete also has CEN technical committees:

- CEN/TC 94 Ready-mixed concrete – production and delivery
- CEN/TC 104 Concrete and related products

Concretes are categorised under a system of exposure classes to demonstrate resilience to difference environmental conditions. National requirements and constraints on the use of the different exposure classes vary slightly between EU Member States.

5.2.2 Recycling

Construction and demolition waste (CDW) accounts for 25% - 30% of all waste generated in the EU. Concrete makes up a significant portion of this, alongside other construction materials. The level of material recovery and recycling varies significantly between EU Member States, from 99% in the Netherlands down to less than 10% (Finland and Cyprus)[57].

The need to return concrete to the production cycle by recycling concrete as an aggregate is likely to increase in importance in the medium term, given that much of the infrastructure in Europe is now mature and will at some point need to be replaced. Currently, recycled concrete aggregate (RCA) is primarily used for road construction, foundations and backfilling. RCA can have improved compaction and density as well as being cheaper than primary mineral aggregates[58].

Small amounts of RCA are also used as an aggregate in making concrete; however, if RCA is used the amount of cement binder may need to be increased in the mixture, as RCA has a higher porosity and this could otherwise result in an impaired mechanical performance of the concrete. Additional and stronger cement is also needed if the original concrete is of a low grade (as may be the case for buildings demolished early due to quality concerns). If the quality of the RCA can be improved by reducing its porosity, it could be used more widely and in greater amounts as an aggregate substitute, ultimately reducing the embodied CO_2 in concrete. Other aggregate substitute materials in concrete have been proposed such as powdered glass and even plastics, but these also can only be used in limited quantities.

The hardened cement component within concrete can be recovered, via separation from crushed, used concrete, and recycled as a raw material for clinker production. Use of recycled cement in raw meal is at trial stage. Laboratory and industrial pilots have demonstrated incorporation up to 15%, and up to 22% may be feasible with further developments, depending on the silica or alkalis contents of the recycled cement[59]. Information on the impact on CO_2 emissions is not provided. The grinding of recovered cement will lead to an increase in electricity consumption compared to preparation of standard raw materials. The challenge is that current separate technologies require further development to allow for more efficient separation to provide recovered cement of sufficient purity from concrete and other construction materials. This could be facilitated by building design and techniques that plan in easy separation of demolition waste.

Concrete slowly reabsorbs CO_2 from the air, at its surface, particularly when moist and carbonation occurs as the CO_2 reacts with the calcium oxide in cement. During the working life of the concrete 5-20% of the CO_2 emitted during the cement manufacturing may be captured[60]. An advantage of RCA is

---

[57] European Commission, 2019, Construction and Demolition Waste (CDW) https://ec.europa.eu/environment/waste/construction_demolition.htm
[58] CEMBUREAU Recycling concrete https://lowcarboneconomy.cembureau.eu/5-parallel-routes/downstream/recycling-concrete/
[59] Interreg North-West Europe SeRaMCo, 2018, Use of recycled aggregates for cement production. https://www.nweurope.eu/projects/project-search/seramco-secondary-raw-materials-for-concrete-precast-products/news/use-of-recycled-aggregates-for-cement-production/
[60] CEMBUREAU, 2018, The role of cement in the

that it will be carbonated more rapidly than the concrete in structures, as it has a greater surface area once crushed. Exposing RCA for a period of months to allow this recarbonation to occur before it is used as in foundations and backfilling provides the opportunity for an additional 5-10% of the CO_2 emitted during the cement manufacturing to be absorbed[60].

The ‘FastCarb’ project[61] starting in 2018 is investigating how this process can be achieved industrially and more rapidly. It is reported that RCA re-carbonation can be accelerated by using the exhaust gases from a cement kiln, which have a higher CO_2 content and are also at a higher temperature, thereby increasing the CO_2 captured by up to 50% of process CO_2 emissions. Such re-carbonation is assessed as being at TRL 7 (full sale demonstration tests) and is not expected to contribute to reduce emissions until after 2025.

5.2.3 Replacing cement in construction

The cement sector in Europe is also developing new types of ‘low carbon’ cement as alternatives to OPC. These broadly use the same raw materials as conventional cements, but their processing is different as they have lower clinker burning temperatures. Preliminary results have shown a reduction of 25-30% in the amount of carbon dioxide being produced[62]. Suitable applications for such low carbon cement binders and mixes are currently being defined i.e. they are at a real-life demonstration stage (TRL>6) but have not yet been commercialised; their adoption long-term will depend on how well they are received by the construction industry.

Other types of non-limestone-based cements that have lower embodied CO_2 emissions have also been investigated as alternatives to OPC, with mixed results. Geopolymer cements are commercially available but use some of the same substitute raw materials used in OPC manufacture, whilst to date magnesium silicate cements[63] have not progressed further beyond lab validation (i.e. TRL 4).

Overall concrete usage in construction could also be further reduced by replacing concrete and steel framed systems with timber-based systems, such as timber frame and glued laminated timber (glulam) structures. The timber should be sourced from sustainably managed forestry. Preparation of the timber may include kiln drying as well as production of the glue and other materials used in the composite, so the timber is not a CO_2 neutral material but there is opportunity for lower embodied carbon than that of reinforced concrete.

Glulam has high load bearing capabilities and dimensional stability and can be manufactured in a wide range of beam and truss forms and configurations; it is used for structural components that can be manufactured in lengths of up to 50 metres and up to 4.5 metres wide[64], meeting the requirements for most larger industrial and commercial buildings. Whilst most buildings foundations’ use concrete, the building frame, roof, walls and floors can all be made from engineered wood products, displacing concrete or steel that would otherwise be used in their construction. Glulam beams are often paired with cross laminated timber (CLT) spanning panels in roof construction.

Engineered wood products give rise to a lighter weight construction and can be pre-assembled for completion on site. Such buildings reportedly have faster construction times with far fewer site deliveries compared to those required for the construction of a concrete framed building – just 15% of

---

2050 low carbon economy. https://lowcarboneconomy.cembureau.eu/wp-content/uploads/2018/09/cembureau-executive-summary.pdf

[61] FastCarb. See: https://fastcarb.fr/en/home/ and https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf

[62] Cement binders made up of Belite, Ye’elimite and Ferrite phases (BYF cements). For example, the ‘Ecobinder’ and ‘Aether’ projects. See: http://www.ecobinder-project.eu/en/ and http://www.aether-cement.eu/

[63] Imperial College developed a carbon negative binder based on magnesium oxide derived from magnesium silicate containing rock such as olivine or basalt. This invention was spun out as ‘Novacem’ in around 2007 but has not been further commercialised.

[64] Structural Timber Association. See: https://www.structuraltimber.co.uk/timber-systems/glulamclt

those for a concrete frame[65]. Additional benefits include improved insulation and high standards of air tightness, which improve the longer term in-use performance and energy efficiency of the building.

5.2.4 Building design

The global availability of concrete alongside its physical properties (mechanical strength and fire resistance), flexibility in application, design and the resulting range of types and forms possible, mean that buildings constructed from concrete are well suited for adaption or disassembly and reuse in a circular economy paradigm; two inter-related measures for this are 'design for adaption' and 'design for reuse'.

In 'design for adaptation' the planning and design stages are important for considering how buildings could in future be refurbished for new functions, once they are no longer in-use, for example, designing an office space that could easily be converted into accommodation.

In 'design for disassembly' concrete building components and materials are produced so that they can be removed more easily, e.g. by using stainless steel fastenings to facilitate their subsequent reuse. Common modular building elements such as columns, walls, beams and slabs can be designed to be disassembled in their entirety without material loss or compromising their structural integrity, in order to be reused in other buildings elsewhere.

This not only avoids the emissions associated with demand for the production and transport of cement but also the purchase cost.

Many of the guidelines produced for design for adaption are in accordance with those for design for disassembly, emphasising ease of dismounting, simplicity of construction, repetition and transparency. Common architectural design concepts that have a relevance to the circular economy include ease of accessibility (for every person), open plan (to enable the further adaption of interiors), expansiveness (to allow for further and possibly unforeseen uses of the building to be realised or created), and effectiveness (in terms of function, cost and quality).

5.2.5 Building codes

Use of lower CO_2 intensity cements (e.g. including recycled content and substitutes) and alternative materials can be incentivised through requirement or reward for the construction sector measuring the embodied carbon and minimising this through selection and efficient use of materials.

For certain types of large infrastructure projects, the EU Environmental Impact Assessment Directive (2014/52/EU) allows for authorities to require calculation and minimisation of lifecycle greenhouse gas emissions as part of consideration in the authorisation process.

More widely, under the EU Circular Economy Action Plan the European Commission, in co-operation with industry stakeholders, is developing "Level(s)". This is a voluntary reporting framework to measure the sustainable performance of buildings across their whole life cycle. This includes indicators for materials use, lifespan, adaptability, deconstruction and demolition waste with a lifecycle assessment tool.

Several Member States already have national, voluntary building codes for environmental assessment. Germany has a mandatory assessment "Bewertungssystem Nachhaltiges Bauen" (BNB)[66] for new federal buildings which includes a whole building life cycle assessment (LCA). Similarly, Netherlands' Building Decree 2012 requires LCA for new homes and non-domestic buildings over $100m^2$. In both cases the requirement is underpinned by a national LCA database, calculation rules, and weighting for different environmental impacts, so score against performance limits. France, UK, Finland are moving towards similar mandatory requirements.

---

[65] Structural Timber Magazine. Winter 2019. Pursuing CLT construction. See: https://issuu.com/radarcommunications/docs/st_mag_issue_18_winter_-_web_file?e=15424601/67698860

[66] https://www.bnb-nachhaltigesbauen.de/

6 Carbon capture, utilisation and storage (CCUS)

While there is potential for reducing demand for cement, as described in Section 5, production can be expected to continue beyond 2030. The process emissions associated with clinker production are largely unavoidable, a consequence of the chemical reactions that occur during the transformation of the raw materials into the desired product, and therefore deep decarbonisation of the sector will depend on capturing of those emissions for storage or utilisation.

6.1 Development of Carbon Capture and Utilisation

6.1.1 The European Development Landscape

Over the last five years there has been a concerted effort within Europe to develop technologies capable of capturing CO_2 from the production of cement clinker. Underpinning this resolve is the fact that, irrespective of the level of consumption of renewable fuels in clinker production and improvements in energy efficiency, appreciable levels of CO_2 generation remain due to the unavoidable emissions from the calcination of limestone, which is central to the clinker production process. Therefore, the continued production of Portland cement presents an obstacle to countries' realisation of ambitious CO_2 reduction goals, unless the process emissions can be addressed via carbon capture.

Beginning in 2015, the CEMCAP project, funded by the European Commission's Horizon 2020 programme, set about to prove and develop a basket of technologies capable of capturing CO_2 from clinker production. The aim of this programme was to prepare the ground for large scale carbon capture from cement production in the EU and specifically to advance each technology's components to real life pilot tests (TRL6). The focus of the programme was on technologies that could be retrofitted into existing cement plants. The rationale for this focus is the fact that, in Europe at least, owing to the mature nature of the industry, there are unlikely to be significant numbers of new cement plants built in the coming decades. Moreover, since cement plants have operating lifetimes of 30-50 years, existing plants are locked in and significant reductions in CO_2 emissions will have to be made at these plants.

The CEMCAP programme ran until the end of 2018 and succeeded in carrying out pilot studies which tested and proved the performance of individual components of a number of CO_2 capture systems. These activities resulted in a number of technology systems becoming ready for demonstration at actual cement sites. These demonstrations are ongoing.

In addition to the developments coming out of CEMCAP, separate development programmes have been pursued, such as the Low Emissions Intensity Lime & Cement "LEILAC" project which, like the CEMCAP programme, is funded under the Horizon 2020 programme, and those under the Norwegian CLIMIT programme.

6.1.2 Carbon Capture Technologies Under Development in Europe

In this section we provide a summary of the carbon capture technologies and approaches being developed within Europe. A range of different technologies are being researched and at this stage each option presented here has potential for further development and possible application. Further details are provided in Appendix A2 which summarises the salient pilot and demonstration plant activity that has taken place and is ongoing in Europe, presented according to the capture technology type. It sets out where the activity is taking place, the partners involved, results to date, abatement cost, outstanding challenges and future plans to overcome challenges and move the technology forward in terms of demonstrating at scale.

Chilled Ammonia Process (CAP)

This is a post combustion capture technology using a solution of ammonia and water (aqueous ammonia) as the CO_2 absorbing agent. After cooling and conditioning, the flue gas from the clinker kiln passes through an absorption column of aqueous ammonia. The CO_2 in the flue gas is absorbed by the solution. The aqueous ammonia solution is regenerated via the application of heat (steam) at pressure, which separates the CO_2 from the solvent. The CO_2 thus released is a very pure stream which can be compressed for subsequent use or storage.

Under CEMCAP, experimental work was carried out at GE Sweden Technical Centre, Växjö Sweden. This work entailed a large pilot scale investigation of the applicability of this technology to the cement process, the development of a thermodynamic and kinetic model and process optimisation for cement production. CAP is now ready for site demonstration.

Advantage with this absorbent is that ammonia is a commodity chemical, available in large quantities globally and is chemically stable. The ammonia is recirculated in a closed loop system,

Membrane Assisted CO_2 Liquefaction (MAL)

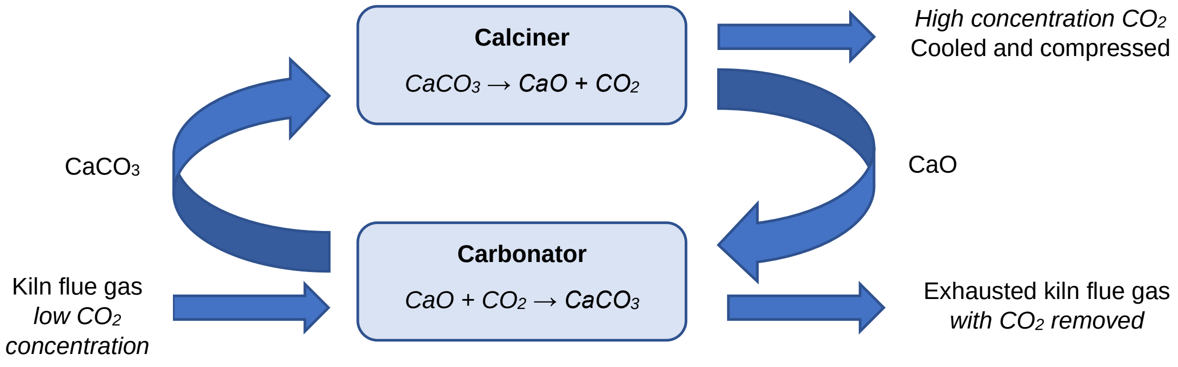
This is another post combustion capture technology and uses CO_2 selective polymer membranes to concentrate the CO_2 in the flue gas before compressing, cooling and condensing. The concentration of the CO_2 is to levels at the lower end of those achieved with oxyfuel firing (see later), i.e. 60-70% and this improves the economics of compression.

Under CEMCAP, lab testing of the membranes has been carried out, and those capable of showing the desired selectivity between CO_2 and nitrogen at the CO_2/nitrogen ratios found in clinker kiln flue gases have been identified. Pilot scale demonstration of the liquefaction process has been achieved at 5-10 tonne/day and very high purities of CO_2 (up to 99.8%). The process schemes for putting together the membrane and liquefaction components has been worked out.

Calcium Looping Capture (CaL)

This post combustion process utilises the properties of Calcium Oxide (CaO) and Calcium Carbonate ($CaCO_3$), specifically the fact that $CaCO_3$ decomposes into CaO and CO_2 when heated and CaO and CO_2 react with each other to form $CaCO_3$ and release heat. The former is carried out in a calciner using heat derived from oxyfuel firing, so that the CO_2 stream created via calcination is very pure. The additional fuel consumed means that there is heat available over and above that available from normal kiln operations which can be recovered and used to generate steam and power. The CaO so produced is then sent to another chamber known as the "carbonator", through which flue gas from the clinker kiln is passed. The CO_2 in the flue gas reacts with the CaO in the carbonator to form $CaCO_3$, which is then sent back to the calciner for the application of heat and the release of the CO_2. The result is a concentrated CO_2 stream. By repeating this loop, dilute CO_2 in the exhaust gas is transformed into a highly concentrated CO_2 stream emanating from the calciner, which can then be cooled and compressed.

Figure 5 Calcium looping cycle



Under CEMCAP, this has been investigated at the University of Stuttgart and two configurations have been studied: (1) tail end, and (2) Integrated entrained flow.

With the tail-end technology, high capture rates of up to 98% have been achieved and the technology is now undergoing site demonstration at La Pereda, Spain. As it is fitted on to the end of the exhaust flue there is potential for retrofit to existing kilns with minor modification.

For the integrated entrained flow technology, a spin off on-site demonstration is being undertaken outside of CEMCAP, funded by Horizon 2020 at Vernasca, Italy (see Appendix A2). The CaL units are integrated alongside the pre-calciners. This approach is less well advanced than the tail-end configuration, but a lower fuel consumption is claimed by the developers.

Oxyfuel

This technology eliminates nitrogen in the combustion products from the cement kiln by using oxygen to support combustion rather than air. The much purer CO_2 stream from the kiln can then be more easily and economically processed for capture and storage.

There are three relevant component changes required to enable oxyfuel combustion: the burner, calciner and clinker cooler. The burner design and operation must be adapted to provide the same temperature profile necessary for high quality clinker formation in the kiln, allowing for the reduced volume flow rate due to the absence of nitrogen when using oxygen rather than air. The kiln gases pass through the calciner, and therefore the reduced volume flow rate and higher CO_2 concentration in these gases affect the reactions occurring in the raw material calcination. The system design must allow for suitable temperature and residence time for adequate decarbonisation of the limestone without formation of any problematic deposits. Similarly, the clinker cooler must be adapted to operate with the higher CO_2 concentrations in the recirculated exhaust gases, as the gas composition affects the cooling rate which influences the product quality as well as the energy efficiency.

Under CEMCAP there was successful testing of an oxyfuel burner and of entrained flow oxyfuel calcination, both in the lab but under conditions typical of clinker production. A third component for the realisation of this technology, clinker cooling using recirculated CO_2, known as an oxyfuel clinker cooler, was tested at the Heidelberg Cement plant at Hannover, Germany.

Analysis of resulting clinker revealed some small levels of clinker alite decomposition, probably due to the moisture content of recirculated CO_2. As such, further work to reduce this and minimise false air ingress is needed and these are being investigated in industrial scale demonstrations at cement plants at Colleferro, Italy and Retznei, Austria.

Low Emissions Intensity Lime and Cement (LEILAC)

This is a direct capture process, whereby the process emissions CO_2 from the calcination of limestone is directly captured from the calciner. To make this possible, calcination takes place in a tube reactor which is heated from the outside, causing the limestone to be indirectly heated. This heat, when transferred to the interior of the reactor, causes the calcination of a limestone stream falling slowly through the reactor. The resulting CO_2 passes out the top of the reactor and the now calcined limestone, in the form of CaO, passes out of the bottom. The CO_2 stream passing out of the top of the reactor is very pure, since it has no diluting and contaminating fuel combustion emissions as occur for directly heated calciners. The CO_2 is then suitable for storage. Combustion emissions are not captured, so either biomass fuels must be used or alternative carbon capture techniques applied to remove the CO_2 from the combustion exhaust.

The reactor at the centre of this technology has been developed by the Australian company, Calix, who have already proved it at the much lower calcining temperatures necessary for magnesium oxide production from magnesite ($MgCO_3$) at a site at Bacchus Marsh, Victoria, Australia.

Development of the project in Europe has been partly supported by the EU's Horizon 2020 programme. A FEED[67] study was completed in 2017 in respect of a pilot plant to be built at the Heidelberg Cement plant at Lixhe, Belgium. Testing of the pilot plant is ongoing, but it has been demonstrated to date that the higher temperatures necessary to calcine limestone can be achieved

---

[67] FEED stands for Front End Engineering Design. The FEED is basic engineering which comes after the Conceptual design or Feasibility study.

and sustained in the reactor, that CO_2 is successfully separated from the limestone and that there are no negative impacts upon the operation of the host plant. The pilot plant is currently processing 5% of the plant's raw meal requirements and the pilot trials are due to complete at the end of 2020, at which point a scale-up roadmap will be produced. There are plans for a larger scale demonstration plant at another yet to be identified European cement plant, where up to 20% of the plant's CO_2 will be captured using this technology.

Norcem, Norway -Post Combustion Capture using amine solvent

Under support from the CLIMIT programme of the Norwegian Government, a FEED study for post combustion capture is being carried out at the Norcem plant at Brevik, Norway. The plant will use amine solvent to capture CO_2 from a cooled and conditioned flue gas from the clinker kiln. This will take place in an absorber. The CO_2/amine solution will then be pumped to a desorber, where the mixture will be heated using low pressure steam generated from heat recovered from the clinker kiln. This will drive off the CO_2, thus regenerating the amine solvent for reuse. The CO_2 driven off will be pure and will be compressed, dried and cooled, thus producing liquid CO_2. Liquid CO_2 will be transported to a storage facility, pending transport via pipeline for storage under the North Sea. As a result of this, about 400 ktonne CO_2 emissions will be avoided from this plant.

6.1.3 European Activities Relating to Carbon Utilisation

The quantities of CO_2 originating from the production of cement clinker are significant and, as mentioned above, even if the CO_2 emissions from fuel consumption are eliminated by using 100% renewable fuel, the CO_2 from limestone calcination remains. For each tonne of Portland cement clinker produced, about 0.53 tonnes of CO_2 arise from limestone calcination. In 2018 120 Mt clinker was produced in the EU28, implying that, at current production levels, there is an irreducible 64 Mt of CO_2 emissions until carbon capture technology is commercially available at cement sites.

The current status regarding the development of carbon capture technologies applicable to clinker production in Europe is discussed in the sections above. Once captured, the question remains about what to do with the CO_2. Storage is an option, provided there are suitable geological sites available close enough to the CO_2 source for this to be technically and economically feasible. However, utilisation of the captured CO_2 is also an option and in this section we briefly consider the current thinking and work in Europe associated with the utilisation of CO_2 captured from cement clinker production.

Under the CEMCAP project, the opportunities for CO_2 utilisation in a diverse range of 16 products was considered. These products ranged from mineral products such as ground calcium carbonate, through to building products (e.g. carbonated concrete), through to fuels (e.g. methane, ethanol) to the use of CO_2 in the food industry and in greenhouses for enhanced growing. The technical feasibility was considered in terms of the additional energy that would be required for the product conversion (the lower the better) and the technology readiness level of the process (the more mature the better). The economic feasibility was also considered in terms of the size of the market of the product in question (the bigger the market the better the sequestration case) and the price of the product in the market (the higher the better, as this make the sequestration potentially more profitable),

This CEMCAP project analysis concluded that compared against the cost of storage of captured CO_2, the case for utilisation is limited due to unfavourable combinations of product value, energy demand in conversion and size of market for the product. It was found that there would be a commercial case for, at most, 10% of the CO_2 captured from a cement plant being utilised in the products studied, with some increase in this for niche cases, where specific circumstances could justify the utilisation of CO_2 in a product where, ordinarily, this would not be justifiable on a commercial basis. This highlights the vital role of CO_2 storage in addressing the problem of CO_2 emissions from cement clinker production.

6.2 Transport and storage

Initial CCS projects have been focused on industrial clusters where the supply and concentration of CO_2 to be captured is high. From these industrial hubs, an infrastructure of pipelines is the most efficient way of transporting CO_2 in large quantities. As these initial projects are publicly supported, the pipelines will likely be open to all operators wishing to store captured CO_2. At a smaller scale, CO_2 may be transported by road tanker or ship. These transport options are well proven as CO_2 is transported in such ways already for commercial purposes (e.g. for the chemicals, oil & gas and food and drink industries).

Box 2. CCS clusters

Four industrial cluster projects have been identified as promising for CCS demonstrations:

- the Porthos Project at a major industrial cluster in the Port of Rotterdam
- the Northern Lights project in Norway which aims to be an open-access hub for companies to deliver captured CO_2 for storage
- the Teesside region in the UK, aiming to be the UK's first decarbonised industrial cluster
- the Acorn project, aiming to deliver a low-cost CCS system in north east Scotland by 2023

Initial storage opportunities for CO_2 are focused on using depleted oil and gas reservoirs, given the existing infrastructure can be adapted and the geological features are already well understood. Storage in saline aquifers, coal seems, shale or salt caverns is considered to be possible but has yet to be demonstrated.

CO_2 can be injected into these porous geological formations, which, at several kilometres underground, are at such temperature and pressure that the CO_2 will be a dense, supercritical fluid, A layer of impermeable cap rock above the reservoir traps the CO_2. Some of the CO_2 may slowly dissolve into water contained within the geological formation, or over many hundreds of years may react with minerals in the surrounding rock to form carbonates, which reduces the risk of leakage over longer timescales.

Using CO_2 for enhanced oil recovery (CO_2-EOR) has the potential to drive down costs of CO_2 storage due to the additional oil revenues generated. EOR is a well-established technique, with examples in USA operating since the 1980s to improve extraction rates and profitability rather than for the purpose of CO_2 storage. The CO_2 used has predominantly been taken from existing underground reservoirs. Application remains low (~2% of global oil production), however the technique is mature and well understood.

Examples of CO_2 storage exist for hydrocarbon reservoirs on-shore (e.g. In-Salah in Algeria) or off-shore (e.g. Sleipner off Norway). Land-based CO_2 storage may be less favourable for storage than off-shore under seabed options due to the difficulty of ensuring safety as a result of the risk of earth tremors as well as the potential risk of ground water acidification. The EU CCS Directive, introduced in 2009, lays down extensive requirements for selecting sites for CO_2 storage and for storage permits to be required before geological CO_2 storage is allowed. It sets the legal framework over the entire lifetime of storage sites to prevent risks to human health or the environment and assigns responsibilities between the operator and Member State. This includes monitoring through the operation of the site and for corrective actions to be taken in the event of leakage. Liability for any damage is set by the Directive on Environmental Liability. Safety and environmental considerations for the capture and transport of CO_2 are mainly covered through the ETS Directive, IED and the Environmental Impact Assessment (EIA) Directive.

The London Protocol, an international agreement on marine pollution and dumping of waste, has historically restricted CO_2 transfer across borders and international waters, and of disposal of CO_2 including by sequestration under the seabed. After more than 10 years of consideration, a recent amendment provisionally allows for cross-border transport of CO_2 to develop providing other requirements continue to be met[68].

---

[68] IMO, 2019, Addressing barriers to transboundary carbon capture and storage http://www.imo.org/en/MediaCentre/PressBriefings/Pages/22-CCS-LP-resolution-.aspx

Appendices

A1 Priority technologies – long list

Option	Brief Option Description	Counterfactual	Scale of Abatement		Scale of Investment (€m)
			Thermal	Electrical	
Clinker Production - Raw meal alteration					
Use of raw meal with lower calcium carbonate content (lower lime saturation factor)	Reduction in the amount of calcium carbonate in the raw meal leads to less calcination CO_2 per unit mass of clinker produced. It also produces a raw meal with better burnability which, therefore, means lower burning temperatures and thermal savings. Clinker thus produced has a lower alite composition and this lowers early strength of the concrete, which will be a disadvantage in a number of applications. This lower early strength can be ameliorated by grinding the clinker to a higher degree of fineness, but this implies a higher grinding energy penalty.	Clinker compositions with higher alite content (promoted by higher calcium carbonate use in raw meal) than is necessary for the early setting strength required.	Decrease of 119 to 125 MJ/tonne cement	Increase of 9 to 25 kWh/tonne cement, depending on additional grinding that is undertaken to offset the lower initial strength of concrete.	None
Use of mineralisers in raw meal to promote clinker formation at lower temperatures.	The addition of mineralisers to the raw meal promote the formation of clinker at lower temperatures. Some mineralisers also lower the dissociation temperature of calcium carbonate, thereby lowering the energy requirement for calcination. The availability and cost of suitable mineralisers may be a barrier to adoption of this option and the grindability of clinker may deteriorate, leading to increased electricity consumption.	Standard raw meal compositions	Decrease of 50 to 180 MJ/tonne clinker	Increase of 1 kWh/tonne clinker (reduced grindability)	None, but there will be additional operational costs for sourcing the mineraliser material.
Clinker Production - Kiln System					
Adopt preheaters and precalciners	Kilns with cyclone preheaters (3 to 6) and precalciners are State of the Art (SoA). These improve the thermal efficiency of clinker production by increasing the calcining efficiency by using exhaust gases to dry and preheat the raw meal.	Long wet or long dry kilns (w/o preheaters and precalciners)	Depends on what it is replacing. Replacing long dry kiln with SoA 5 stage cyclone preheater and precalciner could save 2,000 MJ/tonne clinker.	Decrease up to 5 kWh/tonne clinker	Can be retrofitted to long dry or long wet kilns at €70-100 million (indicative)

Option	Brief Option Description	Counterfactual	Scale of Abatement		Scale of Investment (€m)
			Thermal	Electrical	
Switching from coal (or petroleum coke) to a lower carbon fossil fuel such as oil or natural gas	Using fuel oil or gas as the kiln fuel instead of coal (or pet coke) reduces the combustion related CO_2 emissions from the clinker burning process, since these are lower carbon fuels.	Coal or petroleum coke fuelled kiln	Depends upon whether coal is being replaced with oil or gas - it may increase or decrease. Decrease 40 to 60 kg CO_2/tonne clinker	Assumed to be the same	€5-15 million, for clinker capacity of 2 million tonnes p.a.
Switching from coal (or petroleum coke) to waste or biomass fuels	Using waste or biomass as the kiln fuel instead of coal (or pet coke) reduces the combustion related CO_2 emissions from the clinker burning process, since these are lower carbon fuels. However, the extent of substitution with these fuels is limited for technical reasons, such as alternative fuel calorific value and the presence of undesirable trace elements such as chlorine. The lower calorific values of biomass and waste fuels mean that the level of substitution in the main kiln burner is limited, but the lower process temperatures in the pre-calciner mean that higher levels of alternative fuel substitution can be achieved in this part of the kiln system. The thermal energy requirement typically increases with the use of these alternative fuels due to higher moisture contents.	Coal or petroleum coke fuelled kiln	Increase of 200-300 MJ/tonne clinker. Decrease of 30-50 kg CO_2/tonne clinker - but highly dependent on the level of substitution	Increase of 2-4 kWh/tonne due to higher exhaust fan consumptions needed to move a greater mass of combustion products.	€5-15 million, for clinker capacity of 2 million tonnes p.a.
Kiln System and Clinker Cooler					
Recovery of heat from kiln or clinker cooler to generate power using one of the following: Steam Rankine Cycle, Organic Rankine Cycle or Kalinia Cycle (NH_3 working fluid).	Feasibility depends on the moisture content of raw material. Where this is high, there will be less surplus heat available for generating power via these routes. Traditionally considered for steam Rankine and growing interest for ORC. Uncertain for Kalinia cycle. All power consuming processes - most notably clinker grinding, cooler fan, kiln exhaust fan, ID fan)	Surplus heat not used for power generation	N/A	Decrease of 5 to 22 kWh/tonne clinker	€15-25 million, for clinker capacity of 2 million tonnes p.a.

Option	Brief Option Description	Counterfactual	Scale of Abatement		Scale of Investment (€m)
			Thermal	Electrical	
Clinker Cooler					
Use grate coolers instead of planetary or rotary coolers	Allows for more of the heat contained in the clinker to be recovered for use in other processes. Heat recovered from clinker cooler is typically used to preheat combustion air. Additional heat recovery, facilitated by use of grate coolers, could be used to dry raw materials and, if heat still in excess, generate power.	Planetary or rotary coolers	Decrease of 100-300 MJ/tonne clinker.	Increase of 1 to 6 kWh/tonne clinker	Highly variable €1-20 million for a 6,000 tone/day clinker plant.
All systems					
Application of variable speed drives to motors	There are many motor applications on cement sites where significant variations in load occur. Significant examples are the motors for the induced draft fan, clinker cooler fan and exhaust kiln fan. Where VSDs are not used control is achieved using inefficient methods such as dampers, which wastes energy.	Fixed speed motors operating at partial load	N/A	Decrease of 3-9 kWh/tonne cement	€0.25m to €0.35m per 1 MWe of capacity driven by VSD.
Clinker Grinding/Raw Meal Grinding					
Use Vertical Roller Mills instead of ball mills to grind raw meal and clinker	Less electrical energy input is required to mill material with VRMs compared with ball mills. With VRMs, the electrical energy input is used more directly for the creation of new surface area required when materials are milled.	Ball mills	N/A	Decrease of 5 to 14 kWh/tonne cement	€20-30 million (new installation only)

Option	Brief Option Description	Counterfactual	Scale of Abatement		Scale of Investment (€m)
			Thermal	Electrical	
Clinker Substitution					
Use of fly ash as clinker substitution	Fly ash is obtained from the electrostatic or mechanical precipitation of dust-like particles from the flue gas of furnaces burning coal. It is an alternative cementitious material to clinker produced in a cement kiln. Its use therefore decreases the amount of clinker that must be produced for a given level of cement production. The emissions associated with the production of the displaced clinker are therefore avoided. The extent to which this clinker substitution is possible is a function of the cement's end application. The short-term strength of concrete using cements with fly ash may be decreased significantly, making it unsuitable for some applications. Fly ash is used in very different amounts in different countries of the world.	Cement composition with a higher than necessary clinker content for the intended end application	Decrease of up to 360 MJ/tonne cement (for 25%-35% of cement mass being fly ash)	decrease of 2 to 15 kWh/tonne cement	€8-12 million for 2 million tonne clinker per year plant for extra storage and equipment for handling - assuming up to 35% fly ash mass in cement.
Use of Ground Granulated Blast Furnace Slag (GGBS) as clinker substitution	GGBS is the ground slag by-product from the production of pig iron in blast furnaces. It is an alternative cementitious material to clinker produced in a cement kiln. Its use therefore decreases the amount of clinker that must be produced for a given level of cement production. The emissions associated with the production of the displaced clinker are therefore avoided. The extent to which this clinker substitution is possible is a function of the cement's end application, where there will be specific requirements on setting time, heat generated during setting, short term strength developed, etc., which in turn are affected by the proportions of clinker and GGBS. GGBS is used in quantities ranging from 30 to 70% by mass of cement.	Cement composition with a higher than necessary clinker content for the intended end application	Decrease of up to 1590 MJ/tonne cement	Increase of up to 10 kWh/tonne cement, due to additional grinding requirements	€5-10, for 2 million tonne per year clinker plant for up to 70% GGBS mass in cement. This is very dependent on site circumstances and whether extra storage capacity is required for GGBS. Additional investment is also needed for extra equipment for handling and drying GGBS.

A2 Pilot and demonstration plants for carbon capture from the cement clinker production in the EU

Type	Post combustion capture	Oxyfuel combustion (partial)	Oxyfuel combustion (full)	LEILAC direct separation
Start date	July, 2016	2009	2016	2019
Location	Norcem, Brevik, Norway	FLSmidth R&D pilot plant in Dania, Denmark	HeidelbergCement Plant in Hannover, Germany	Lixhe, Belgium
Scale	1.2 million tonnes of cement per annum The Brevik site has two point sources, corresponding to the two clinker production trains, with combined emissions of approximately 925 kt/y of CO_2.	30−50 tpd	80 tpd	240 tpd
Current status in terms of Technology Readiness Level (TRL)	7	6	6	6-7
Technology description	There are a number of post combustion capture technologies available which have been tested at Norcem, Brevik, Norway. These include: - Aker Solutions amine technology - Air Products/ NTNU membrane technology - RTI solid sorbent technology - Alstom Power Calcium Looping	The aim was to integrate the CO_2 capture technology into the cement plant by implementing the oxy-combustion at calciner Air is replaced by oxygen injection at calciner while the combustion gases get partially recycled to the calciner	Part of the hot clinker from a running rotary kiln is extracted and supplied to a 80 t/d cooler prototype. A set of different parameters such as different cooling gas compositions, mass and gas load, operating modes of the grate cooler (bed velocity) were investigated to evaluate the process reliability including the cooling curve and sealing efficiency. Clinker samples produced from the prototype were characterised with regard to the mineralogical composition in order to evaluate the impact of the changed gas atmosphere and correspondingly the cooling rate on the clinker quality.	The LEILAC project aims to enable the efficient capture of the unavoidable process emissions from lime and cement production Calix's technology re-engineers the existing process flows of a traditional calciner, indirectly heating the limestone via a special steel vessel. This unique system enables pure CO_2 to be captured as it is released from the limestone, as the furnace exhaust gases are kept separate.

Type	Post combustion capture	Oxyfuel combustion (partial)	Oxyfuel combustion (full)	LEILAC direct separation
Project partners	Norcem (Heidelberg Cement Group), Aker Solutions	Air Liquide, FLSmidth, and Lafarge,	HeidelbergCement, European Cement Research Academy (ECRA), CEMCAP (funded by European Union under Horizon 2020 programme), VDZ	HeidelbergCement, LEILAC (funded by European Union under Horizon 2020 programme)
Key findings to date	Testing on 4 capture technologies on real flue gas have been performed under the CLIMIT programme at the Brevik plant: - Aker Solutions amine technology - Air Products/ NTNU membrane technology - RTI solid sorbent technology - Alstom Power Calcium Looping In a 2020 perspective, Aker Solutions deemed amine technology the only post-combustion technology ready for a full scale project It is expected that use of the plant waste heat will meet 40% of the heat demand for regenerating the amine solvent. The tests and experience has been successful and it is expected that up to 400 ktonnes/annum of CO_2 will be avoided.	• No safety issues regarding oxygen have been experienced during the trials • Stable operation was achieved • Measured CO_2 concentration in calciner was limited to 66 % vol. dry below target 78 % due to false air and limited raw feed rate • Calcined raw meal showed no difference between air and oxy-combustion i.e., no expected impact on cement quality • Results showed that an existing preheater or calciner cement kiln line can be retrofitted to oxy-combustion	- Clinker cooling was successfully demonstrated under oxyfuel conditions in industrial environment - No negative impact on cement strength development due to cooling with CO_2 rich gas - Considerably high false air ingress through cold clinker discharge system outlet. - No leakages of CO_2–rich gas occurred during the trials. - Cooling gas recirculation gave origin to a phenomenon of moisture enrichment. - The microstructure of the clinker samples indicates fast cooling, which may have its origin in the experimental setup (extraction of finer clinker granules from the kiln and high false air ingress). - A few clinker samples showed unusual layers of up to 2 µm thickness around alite crystals in contact with pores (probably very fine grained belite and free lime crystals resulting from up to 4% alite decomposition). - Layer formation cannot be correlated with the high CO_2 concentrations in the cooling medium alone. Thesis: decomposition of alite caused by water in the cooling gas.	Early stages. However, early results look promising, with CO_2 separation occurring, calcined material produced and the tube structure and mechanical expansion holding up.
Estimated cost for capture (€/tCO_2 avoided)	44	49	39	80

Type	Post combustion capture	Oxyfuel combustion (partial)	Oxyfuel combustion (full)	LEILAC direct separation
Outstanding challenges	• The CO_2 quota price level required to cover the cost of the CO_2 capture (not including transport and storage) implementation on the cement plant analysed here is around 60 €/tCO_2. A more stringent CO_2 quota policy is required. However, by itself, this is unlikely to be a sufficient measure to kick-start the implementation of CCS in the cement production industry. Additional incentives will also be required to ensure the viability of CCS from cement production: • Innovative business models at the intersection between the public and private sectors will have to be developed in order to help close the cost gap and align commercial and societal interests across the CCS chain.	Some trials were hindered by poor raw metal flow in the lower part of the preheater	-False air ingress is expected to be one of the big challenges for Oxyfuel technology. Sealing the cooler outlet against false air ingress will demand special attention in industrial scale projects - Moisture and dust content in re-circulated gases to be minimized for a trouble-free operation of the cooler	Problems with thermocouples failing, blockages and recarbonation at the base of the tube have been encountered but these are being tackled in the de-bottlenecking phase.
Future plans	Presently, a front-end engineering design (FEED)-study for the Norcem Brevik plant is being carried out to prepare for a final investment decision by the Norwegian Parliament in 2020/2021. It is hoped the project will then be able to commence operations in 2023/2024.	Technology now ready to move into the demonstration phase • Next stage would be a 1-2 year FEED study	The European Cement Research Academy (ECRA) have outlined plans to implement oxyfuel technology in two cement plants in Europe. HeidelbergCement and LafargeHolcim will dedicate plants in Colleferro (Italy) and Retznei (Austria) respectively to test for the first time how the cement production process can be adapted to accommodate this cutting edge carbon capture technology. The project will require a significant investment volume and will rely on industry contributions, but significant	Testing will continue well into 2020 and plans for the next demonstration project at another cement plant in Europe are already moving ahead. LEILAC 2 will see industry partners Cimpor, Lhoist, Port of Rotterdam and IKN join Calix, HeidelbergCement and other research partners to work together on a larger 0.1Mt/yr CO_2 separation pilot scheduled for completion in 2025

Type	Post combustion capture	Oxyfuel combustion (partial)	Oxyfuel combustion (full)	LEILAC direct separation
			funding from public sources will also be required	
Key sources	https://www.sintef.no/globalassets/sintef-energi/cemcap/11_full-scale_ccs-project_norcem_brevik.pdf/ https://www.sintef.no/globalassets/project/cemcap/presentasjoner/17-oct-2018/10_norcem_brevik_CO_2-capture_project_assessment_post-combustion_technologies_p.brevik.pdf/	https://ieaghg.org/docs/General_Docs/Publications/Information_Papers/2014-IP7.pdf https://www.sintef.no/globalassets/sintef-energi/cemcap/gimenez_ccus_projects-at-lafargeholcimCO_2capture.pdf/ https://www.netl.doe.gov/sites/default/files/event-proceedings/2014/2014%20NETL%20CO_2%20Capture/J-Gale-IEAGHG-Global-Perspective-On-CO_2-Capture.pdf https://www.sciencedirect.com/science/article/pii/S0016236118315059	https://www.sintef.no/globalassets/project/cemcap/presentasjoner/17-oct-2018/8_perspective_on_oxyfuel_capture-technology-application-in-a-cement-plant_v.hoenig_j.ruppert.pdf/ https://ecra-online.org/fileadmin/ecra/press_releases/Cement_Industry_Launches_Industrial-Scale_Carbon_Capture_Project.pdf https://www.heidelbergcement.com/en/ecra-oxyfuel	https://www.globalcement.com/news/item/10379-innovation-in-industrial-carbon-capture-conference-2020 https://9ae48deb-dd3f-4936-9a9f-ed25155caed5.filesusr.com/ugd/ce8a5c_c050d8aca91e4e1d9ba199734e48a720.pdf https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=39572&no=2 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800680/Literature_Review_Report_Rev_2A__1_.pdf

Type	Calcium looping	Calcium looping	Calcium looping
Start date	2017	2017	2018
Location	Spanish Research Council (CSIC-INCAR)	Institute of Combustion and Power Plant Technology at the University of Stuttgart	Vernasca, Italy
Scale	30 kWth	200 kWth	1.3Mt/yr plant

Type	Calcium looping	Calcium looping	Calcium looping
Current status in terms of Technology Readiness Level (TRL)	6-7	6	7
Technology description	A 30 kWth pilot was retrofitted to operate with a higher carbonator CO_2 load, more active sorbent, and smaller particle sizes.	The pilot plant consists of two interconnected refractory lined circulating fluidized bed reactors. Each reactor is 10 m in height and has an inner diameter of 20 cm. The solid flow between the reactors is controlled by the means of two cone valves. The heat required for the calcination is provided by oxy-fuel combustion of hard coal. Hot recirculation gas from the calciner mixed with oxygen is used as oxidiser. The oxidation medium can be fed at three different levels to the calciner. A synthetic flue gas mixture consisting of air, steam and CO_2 is preheated by an electrical preheater and fed to the carbonator.	The project's core activity is the design, construction and operation of a CaL demonstration system that will capture the CO_2 from a portion of the flue gas of the cement plant in Vernasca (Italy), using as CO_2 sorbent the same raw meal that is used for clinker production.
Project partners	Spanish Research Council, funding from CEMCAP and the Spanish Ministry of Economy and Competitively	University of Stuttgart, CEMCAP (funded by European Union under Horizon 2020 programme)	CLEANKER (funded by European Union under Horizon 2020 programme) Coordinator: LABORATORIO ENERGIA AMBIENTE PIACENZA
Key findings to date	The use of materials of low particle size resulted in a lower inventory of solids in the carbonator (as low as 75 kg/m2) at typical gas velocities in the carbonator reactor of the pilot (around 2.5 m/s). Under these conditions, despite the high CO_2 load in the carbonator and low inventories, it is possible to achieve high capture efficiencies (close to the limit allowed by the	The 200 kWth pilot plant at the Institute of Combustion and Power Plant Technology was successfully operated during a 120 h experimental campaign investigating cement specific calcium looping operation conditions. High CO_2 capture rates up to the equilibrium capture were achieved over a wide range of operation conditions. Cement specific operation condition	The project is in early stages. The first one-and-a-half-year main results are related to (i) raw meal characterization, (ii) modelling, (iii) engineering, (iv) CO_2 mineral carbonation, (v) methodology for CCUS scenarios modelling and (vi) regulations. (i) Characterization of the raw meal: experimental tests under conditions as close as possible to those expected in the CLEANKER CaL pilot have been carried out using Vernasca raw meal. Calcination tests in air-blown and in oxyfuel conditions were performed in laboratory EF reactors. In addition, carbonation tests of the calcined material in TGA apparatus were carried out. Carbonation and calcination conversions at different conditions, as

Type	Calcium looping	Calcium looping	Calcium looping
	equilibrium) when there is a high sorbent activity, which is characteristic of calcium looping in cement plants. The apparent carbonation constant rate calculated from all the experimental results in the pilot is 0.36 s–1, which is consistent with the equivalent parameters of previous works aimed at capturing CO_2 from power plants. In summary, the results of this work indicate that CaL technology can be retrofitted to cement plants on the basis of the knowledge acquired with CaL in the more developed systems of power plants.	benefits the calcium looping process due to a highly active bed material resulting from the high amount of fresh sorbent. The synergy effects between the calcium looping CO_2 capture and cement production paired with high CO_2 capture rate even above 95 % suppose a high suitability of calcium looping for CO_2 capture in the cement industry.	well as the belite formation (Ca2SiO4, a stable compound whose formation uses part of the free CaO) and decay constants have been investigated (ii) Modelling of the pilot plant focused on heat and mass balances (D2.3) of the demonstrator under different relevant operating conditions to support the design of the pilot. In addition, new models (D5.3) for the global pilot plant and for the coupled calciner and carbonator reactors were validated. Modelling for raw meal characterization focused on quantifying the kinetics rates of calcination and carbonation. Compared to natural limestones, the Vernasca calcined raw meal presented a complex behaviour as sorbent, mainly due to the formation of belite. The decay constants obtained are shown to be comparable to typical values reported for other standard limestones (iii) Based on modelling activities, the layout of the CaL Vernasca demonstrator was defined. Interconnections to the existing plant, quantification of additional loads to be considered in the existing structures, identification of all measuring devices and drive motors, definition of measurement points and instrumentation and definition of all individual machinery and piece of equipment were detailed (D2.1 and D2.4) (iv) Different waste materials including burnt oil shale, concrete demolition wastes, cement by-pass dust and blast furnace slag sampled from Estonian, Italian and German power plants and Buzzi Cement Plant in Italy were tested via wet direct carbonation method (D7.4). Selected types of burnt oil shale and cement by-pass dust could be used as effective sorbents in the proposed CO_2-mineralization process, binding up to 0.18 kg CO_2 per kg of waste (v) Methodology for techno-economic modelling of the Baltic and Italian CCUS scenarios, including database structure, is developed in D7.1 (vi) International and national regulations related to CCUS technology and their national implementations are studied in detail (D7.3) and compared for the five countries (Italy, Estonia, Latvia, Lithuania and Russia) involved in the planned CCUS scenarios of the CLEANKER project During the first 18 months, particular attention was devoted to the communication activities. The CLEANKER website was launched and CLEANKER is on twitter (@CLEANKER_H2020). In addition, the project has published 3 newsletters and organized public events for the stakeholders of the local community where the demo plant will

Type	Calcium looping	Calcium looping	Calcium looping
			be erected as well as for scientific communities, industry and policy makers interested in CCS.
Estimated cost for capture **€/tCO_2 avoided**	50		
Outstanding challenges	Scale-up required, some experimental variables inherently difficult to measure with precision in this small pilot plant, leading to uncertainties.	Technology still under development Technology might cause problems for the rotary kiln	TBC
Future plans	The results presented in this work lend support to the scalability of this technology for capturing CO_2 in cement plants by using the knowledge acquired in these large facilities.	The technology is now ready for on-site demo. The CLEANKER demonstrator will progress the CO_2 capture from cement plants via CaL technology in industrial environment (TRL7) at La Pereda, Spain. This project started in 2018.	The main goals of the projects are: • CO_2 capture efficiencies higher than 90%, • electric consumption max. 20% higher than in a cement plant without capture (thanks to heat recovery in the CaL process and power generation), • SPECCA below 2 MJLHV/kgCO_2, • keeping the cost of CO_2 avoided below 30 €/tCO_2 • an increase of cost of cement to max. 25 €/t.
Key sources	https://pubs.acs.org/doi/10.1021/acs.iecr.6b04617	https://www.sciencedirect.com/science/article/pii/S1876610217319562?via%3Dihub https://cordis.europa.eu/project/id/764816/reporting	https://cordis.europa.eu/project/id/764816

A3 Emerging techniques for low carbon cement production in the EU

Type	**Use of alternative energy sources to heat cement kiln**		
Start date	2017	2020	2019
Location	Slite in Gotland	UK-sites operated by Tarmac and Hanson	Odeillo, France.
Scale			50 kW solar reactor
TRL	3-4	3-4	3-4
Technology description	CemZero project: The pilot study has examined different technologies for heating in the cement process, with fossil-free electricity used as the energy source instead of conventional fuels.	Mineral Products Association demonstrations of hydrogen and plasma technology The project will demonstrate the potential to reduce carbon emissions through fuel switching from fossil fuels in cement and lime production. The cement trials will take place at sites operated by Tarmac and Hanson Cement. The cement production trial comprises two demonstrations, one of electrical plasma energy and biomass fuel and the other of hydrogen and biomass energy.	This project is developing a pilot scale high temperature (950°C) 24hr/day solar process for energy intensive non-metallic minerals' industries like cement and lime. The pilot used a 50kW solar reactor to test a fluidised bed system at the PROMES (PROcédés, Materials and Solar Energy) testing site in Odeillo, France.
Project partners	Vattenfall and Cementa (part of Heidelberg Cement Group)	Mineral Products Association	10 partners from 7 countries COORDINATOR= CNRS-PROMES, France
Funding bodies	Funded by partners, co-financed by Swedish Energy Agency	UK Department for Business, Energy and Industrial Strategy	European Union Horizon 2020 funding,
Key findings & Potential impacts	The study draws the following principal conclusions: • Electrification of the heating in the cement process appears to be technically possible. Among other things it has been shown to produce a certain amount of cement clinker based entirely on plasma technology. This possibility needs to be verified through large scale testing. • An electrified solution for cement is competitive compared with other alternatives	Project not yet started The key issues to be addressed in study for each fuel switching option for cement are: Plasma: Power supply requirements, Cement kiln specific prototype plasma torch design, Composition and choice of plasma gases, Thermal stress tests of plasma torch electrodes, Optimised location of the plasma burners Hydrogen: Hydrogen delivery system to the	Key outputs: - Demonstration of 800-1000°C on-sun operation of the solar reactors - Demonstration of the storage capacity - Several days (5) of continuous operation - Gas and solid products analysis The SOLPART project also resulted in the development of two new solar reactor technologies, namely the rotary kiln and the fluidized bed that enable continuous solar

Type	**Use of alternative energy sources to heat cement kiln**		
	in order to achieve radical reductions in emissions. The study demonstrates an approximate doubling of the production cost for the cement, but ultimately only entails a cost increase of a couple of per cent of the finished building or infrastructure. • Simulations have indicated that any future electrification of Cementa's factory on Gotland would work well together with planned expansion of wind energy on Gotland, partly through an improved energy balance, but also through reduction of the maximum surplus capacity to which wind energy would otherwise give rise.	kiln burner, Hydrogen compatible prototype burner design/modifications, Empirical observation of flame radiation performance Assessment of the potential for kiln start up on hydrogen, Clinker formation evaluation., Whole life CO_2 assessment of hydrogen use in cement manufacture General: Scale up potential, Emissions impact, Deployment potential	calcination of particles in a wide range of particle diameter from about 5 microns to 500 microns. The possible integration of these solar technologies for lime, dolomite, phosphate and cement industries was studied for calcination capacity ranging from 100 tons per day to 3500 tons/day. Scaling-up issues have been identified and evaluated accounting for the needed sizes of the solar field, the solar reactor and the storage.
Future prospects & Implementation Timescales	Based on these results, Cementa and Vattenfall decided in January 2019 to continue their cooperation on the CemZero project with investigations on the potential for constructing a pilot plant for a climate smart and sustainable cement production process in Sweden. The Swedish Energy Agency has also played an important role in the success of the project and has co-financed the feasibility study.	If successfully demonstrated to be technically and financially viable, this world first of a kind fuel switching could yield emissions savings of as much as 2 million tonnes of carbon dioxide per year at 2018 production rates, if fully implemented across the UK cement industry. This fuel switching option could be implemented flexibly which would enable plants to respond to changing costs and availabilities of electricity, biomass fuels and hydrogen gas. For example, because cement production is a 24hr operation plasma energy could be used at times of low power demand or when there is an excess of renewable generation on the grid.	The project has finished but the results of the project open the route to a demo-scale solar calcination unit with a capacity of about 1-5 ton per day. The developed solar reactor technologies demonstrated their capacity to calcine particles in the range 800-900°C. They can be used in other thermal processes of mineral industries involving particles in a wide range of solid diameter.
Key sources	https://group.vattenfall.com/press-and-media/news--press-releases/pressreleases/2019/vattenfall-and-cementa-take-the-next-step-towards-a-climate-neutral-cement	https://mineralproducts.org/20-release09.htm https://www.gov.uk/government/news/90-million-uk-drive-to-reduce-carbon-emissions	https://www.solpart-project.eu/wp-content/uploads/2018/06/SOLPART-project-presentation.pdf https://www.solpart-project.eu/wp-content/uploads/2020/04/Deliverable-7.1-Summary.pdf http://helioscsp.com/cement-production-with-concentrated-solar-power/

Type	**Clinkered alternative cements**	**Non-clinkered alternative cements**
Start date	2011	2018
Location	Lafarge plant in Burgundy and its Le Teil plant in the Ardèche region	Developed in Cemex's Swiss laboratory.
Scale	"Industrial-scale"	N/A
TRL	6-7	9
Technology description	Through Project Aether, Lafarge has developed a new generation of lower-carbon Aether® cements. These cements can be made from conventional raw materials, in existing industrial installations and offer similar performances to Ordinary Portland Cement, but with 25-30% lower CO_2 emissions. Lafarge is developing Aether® based concretes for a range of ready-mix and precast applications. LIFE+ funding contributed to the running of pilot tests for Aether® cement production at ICiMB facilities in Poland. Lafarge then ran industrial trials at two of its French cement plants, the first in February 2011 at its plant in Burgundy, the second in December 2012 at its Le Teil plant in the Ardèche region.	Vertua is Cemex's new range of low carbon concretes. CEMEX 'Vertua Ultra Zero' clinker-free cement has a c.30-50% CO_2 reduction versus a standard concrete (CEM I) mix. The product is available in a range of compressive strengths from C16/20 to C40/50 and meets the requirement of DC-2.
Project partners	Lafarge (France, Lyon) –co-ordinator, BRE (UK) -partner,RCBM (Poland, Cracovie) -partner	CEMEX
Key findings to date	European Union's LIFE+ programme	N/A
Outstanding challenges	Aether® clinkers can be successfully produced : •in kilns designed for making Portland cement clinker (semi-dry or dry process), •using similar process parameters and fuels, •with conventional raw materials, •at lower temperatures (1250 -1300°C) than for Portland cement clinker (1400 –1500°C), •with significantly lower energy that Portland cement clinker, •Aether® cement grinding energy is also lower than for PC. Assessments during the trials confirm that Aether® generates 20 to 30% less CO_2per tonne of cement than pure Portland cement (CEM (I) type	The chemical structure of Vertua has not been disclosed, other than the fact it has a new "geopolymer" cement, developed in Cemex's Swiss laboratory.

Type	Clinkered alternative cements	Non-clinkered alternative cements
Future plans	While Aether production is similar to PC production, a higher level of control is needed for each process step. In particular, a very narrow temperature range is required in the clinkering zone of the kiln, to ensure that the clinker is neither under nor over burnt, as in either case this reduces the overall amount of ye'elimite and therefore the early strength gain of Aether cements. Furthermore, under burnt clinker leaves an uncompleted combination of the different elements present in the raw meal, while over burnt clinker generates higher SOx emissions, due to a decomposition of the ye'elimite phase. Too high a temperature in the clinkering zone also leads to a risk of ring formation or melting that can force a kiln stop and the over burnt clinker is harder to grind.	Products are commercially available. The Vertua line of low CO_2 products was originally launched by Cemex in France in July 2018. Cemex is working with a carbon offsetting consultant, to make its Vertua low carbon concrete range officially certified CarbonNeutral, in accordance with The CarbonNeutral Protocol, with use of offsetting to deliver net zero carbon concrete.
Key sources	http://www.aether-cement.eu/fileadmin/_migrated/content_uploads/AETHER_laymans.pdf http://www.aether-cement.eu/fileadmin/user/pdf/2014.09.16_BRE_Presentation_Cement___Concrete_Science_Conf.pdf	https://www.cemex.co.uk/documents/45807659/46030023/35273_Cemex_Vertua_Brochure_V13_NO+FSC_spreads+FOR+WEB.pdf https://www.pbctoday.co.uk/news/energy-news/low-carbon-concrete/72344/ https://www.theconstructionindex.co.uk/news/view/cemex-offers-offsetting-to-create-carbon-neutral-cement

T: +44 (0) 1235 753000

E: enquiry@ricardo.com

W: ee.ricardo.com