IEA Bioenergy
Technology Collaboration Programme

Deployment of bio-CCS in the cement sector: an overview of technology options and policy tools

Contribution of IEA Bioenergy Task 40/45 to the inter-task project *Deployment of bio-CCUS value chains*

December 2021

(Photo from Heidelberg Cement)

Bio-CCS in the cement sector: an overview of technology options and policy tools

Otávio Cavalett[1], Francesco Cherubini[1] & Olle Olsson[2]

[1]Norwegian University of Science and Technology (NTNU) & IEA Bioenergy Task 45

[2] Stockholm Environment Institute (SEI) & IEA Bioenergy Task 40

Contribution of IEA Bioenergy Task 40/45 to the inter-task project *Deployment of bio-CCUS value chains*

December 2021

ISBN 978-1-910154-98-4

Published by IEA Bioenergy

Preface

It is becoming increasingly clear that substantial amounts of negative emissions will likely be required if global warming is to be limited to 1.5°C above pre-industrial levels, as is an ambition of the 2015 Paris Climate Agreement. Among the different negative emissions options available, bioenergy with carbon capture and storage, also referred to as bio-CCS (also known as BECCS), is arguably one of the most commonly discussed in climate policy debates.

Bio-CCS has primarily been discussed in terms of its potential and drawbacks over a very long timeframe, e.g., 2050 and beyond, but recent years have seen growing focus on more near-term aspects. The IEA Bioenergy inter-task project *Deployment of BECCS/U value chains* runs 2019-2021 and strives to provide insights about the opportunities and challenges pertaining to taking BECCS from conceptual discussions to on-the-ground implementation. To this end, the project puts focus not only on technological aspects but also on how BECCS business models could be set up and the role that public policy could play in enabling sustainable deployment of BECCS.

An important characteristic of BECCS is that it can be implemented in a broad range of sectors – basically any setting where there are biogenic emissions of CO_2 available in sizeable quantities. This includes generation of heat and power in various contexts, but also industrial facilities like cement production, pulp & paper mills or ethanol plants. The specifics related to BECCS implementation can however vary quite substantially from sector to sector. This is partly because of differences in technological factors like CO_2 concentrations in flue gases, but also a result of how different sectors operate under widely varying commercial and regulatory conditions.

This report is one of a series of publications that are carried out under the *Deployment of BECCS/U Value Chains* project with the aim to highlight these sector-specific characteristics. The sector studies reports provide deeper insights into the key aspects that come into play in the process of practically setting up value chains for capture, transportation and sequestration or utilization of biogenic CO_2.

Summary

Cement is a key input to concrete, the most widely used construction material in the world and upon which many functions of modern society rests. At the same time, production of cement is one of the single most important economic activities in terms of emissions of greenhouses gases. If global climate change mitigation ambitions are to be fulfilled, emissions from cement production will have to decrease by around 95% between 2020 and 2050 according to the International Energy Agency's 2021 Net-Zero report. A broad portfolio of measures will have to be taken to reach this, including energy efficiency improvements, decreased cement demand and an increased use of alternative binder materials. However, it will most likely be impossible to reach deep emission reductions in the cement sector without the implementation of carbon capture and storage (CCS) technologies.

In this report, we review the prospects for implementation of CCS in the cement sector. We give particular attention to the opportunities of combining this with the use of biogenic fuels for process heat, so-called BECCS or bio-CCS. This could prove to be a vital tool to make cement production with net-zero CO_2 emissions possible and could potentially also enable "negative emissions", also referred to as carbon dioxide removal (CDR). In addition to a thorough review of the technological options at hand, we also discuss the business and policy aspects that need to be put in place to enable this.

There are several different technological options available by which bio-CCS can be implemented in the cement sector. Their characteristics vary when it comes to operational aspects and level of investments needed, and these key aspects are discussed in this report. One thing that they do have in common is that it is inevitable that even with cost reductions that come with increasing technological maturity, their introduction will entail substantial increases in the production cost of cement. A key question for cement decarbonization is how these costs should be covered. Here, the fact that a large portion of societal use of cement in one way or another is subject to public procurement means that changing procurement guidelines to mandate low-CO_2 emission cement in publicly funded projects could be a promising policy measure.

Acknowledgments

We would like to thank Johan Rootzén of IVL Swedish Environmental Research Institute and Mari Voldsund of SINTEF Energy(Norway) for valuable comments on an earlier version of this report. Any remaining errors or omissions are the sole responsibility of the authors.

Contents

1 Introduction

Concrete is widely used for construction around the world due to its strong physical properties and the abundance of its raw materials. As demand for concrete has steadily been increasing in recent history, so has demand for cement, which is its main component and functions as the binder in concrete. This has positioned the cement industry as one of the largest energy consumers. In 2014, cement production made up around 7% (10.7 EJ) of global industrial energy use (Pales and Leung 2018; Voldsund et al. 2019). Production of cement is also a large source of carbon dioxide emissions. The more than 4 billion tonnes of cement produced every year in total account for around 8% of global CO_2 emissions, or about 22% of global CO_2 emissions from industrial processes (Preston and Lehne 2018; Sims et al. 2014).

The unique properties that cement provides, combined with the very large volumes used, entail that it is highly unlikely that large-scale substitution away from cement will be possible (Habert et al. 2020). Consequently, the cement sector faces the challenge of continuing to meet demand for its product while cutting direct CO_2 emissions from its production. According to the International Energy Agency's *Net-Zero by 2050* scenario (IEA 2021), global CO_2 emissions from the cement sector need to decrease by more than 94% between 2020 and 2050. An even larger reduction in the emissions *intensity* of global cement production is required, as the IEA sees global production of cement in 2050 being slightly larger than that in 2020.

Bringing about this transformation will require progress across a portfolio of measures, including improving energy efficiency (e.g. use of more energy efficient equipment, replacement of old installations, energy integration), switching to alternative fuels (fuels from wastes and residues, that may be less carbon intensive) and reducing the clinker to cement ratio. (Hills et al. 2016; Preston and Lehne 2018). However, even with successful implementation of these more conventional carbon mitigation measures, specific emissions per ton of cement are likely to decrease only by around 25-50% (Habert et al. 2020; Hills et al. 2016).

A special characteristic of the cement industry is the fact that about 60%-70% of the CO_2 comes from the chemical reactions involved in converting limestone to calcium oxide, a precursor to the formation of calcium silicates which give cement its strength. About 30%-40% of CO_2 emissions result from combustion of fuels and the remaining up to 10% from other downstream plant operations (Pales and Leung 2018; Vatopoulos and Tzimas 2012). Therefore, significant overall emission reductions to bring the cement sector in line with global climate stabilization targets can only be achieved with the integration of emerging and innovative technologies, in particular carbon capture and storage, CCS (Hills et al. 2016; Pales and Leung 2018; Plaza et al. 2020; Preston and Lehne 2018; Rolfe et al. 2018; Vatopoulos and Tzimas 2012). Integration of CCS technologies is identified to provide the largest cumulative CO_2 emissions reductions in the cement industry by 2050 in the sectoral projections in line with the Paris Agreement (IEA 2021; Pales and Leung 2018).

Maximizing efficiency measures and combining CCS with increased use of sustainable biomass as a source of process heat could enable cement production with very low or possibly even negative life cycle emissions of greenhouse gases. However, this requires that not only that the necessary technologies are developed and demonstrated but also that policy frameworks, financing mechanisms and business models are aligned. These are all substantial challenges that need to be addressed urgently for the global cement sector to be compatible with ambitions to reduce global GHG emissions to net-zero by mid-century. This report provides an overview of the prospects for implementation of bio-CCS in the cement sector. In addition to a thorough review of the technological options at hand, we also discuss the business and policy aspects that need to be put in place.

2 Decarbonisation of the global cement industry

2.1 OVERVIEW OF THE GLOBAL CEMENT SECTOR

Cement production intensity levels vary widely across different regions. Some, such as China and the Middle East, have cement production capacity with cement production intensities well above global levels, e.g. 1818 kg of cement produced per capita in China and 827 kg of cement produced per capita in the Middle East in 2014 compared to 575 kg of cement produced per capita globally (Pales and Leung 2018). The global cement market is currently dominated by a fairly small number of large producers, in particular LafargeHolcim (the product of a 2015 merger between Lafarge of France and Holcim of Switzerland), HeidelbergCement (Germany), Cemex (Mexico) and Italcementi (an Italian firm in which HeidelbergCement has a 45% stake). While Chinese companies are leading players in terms of production volumes, they largely operate in their domestic market. Globally, cement firms tend towards vertical integration, producing their own concrete in downstream operations. The capital intensity of cement production reinforces this concentration, making it difficult for smaller actors to enter the market and compete with larger firms. However, the global concrete market is much more fragmented and is built on many smaller companies serving local areas. The key differences between concrete producers lie in how they deliver concrete to the end user (Preston and Lehne 2018).

The major cement players are increasingly facing competition from regional producers in emerging markets. Slower economic growth in China has helped create a global cement surplus, and in Europe there has been a substantial imbalance between high production capacity and low market demand in recent years. The Chinese market is rapidly consolidating: a few years ago, there were 3000 small players producing low-grade cement; by 2020, as few as 10 firms may account for 60% of the country's production capacity. China National Building Material (CNBM) and Sinoma, the country's largest and fourth-largest producers, are merging to become one of the world's largest cement companies (Preston and Lehne 2018).

Significant changes in how cement and concrete are produced and used, and in how cities are designed, built and managed, will be needed if we are to meet the goals set out in the Paris Agreement on climate change as well as the United Nations Sustainable Development Goals (SDGs). All regions in the world have improved the energy efficiency and reduced the carbon intensity of their cement industries. China, India, and the European Union, which are the three largest cement producing jurisdictions, have adopted policy measures to reduce the carbon footprint of the cement industry, through emissions trading schemes, energy efficiency targets, replacement of old plants, new cement standards, and circular economy. Private-led initiatives are also gaining momentum (Preston and Lehne 2018).

In 2015, 18 cement companies established the shared ambition to by 2030 reduce their CO_2 emissions by 20-25% compared to business as usual, which represents a mitigation effort of about 1 Gton CO_2 (Pales and Leung 2018; Plaza et al. 2020). The Global Cement and Concrete Association (GCCA) includes worldwide members that together account for 50% global cement production capacity. In 2019, GCCA launched *Innovandi*, the Global Cement and Concrete Research Network, which intends to research areas such as the impact of co-processing, the efficiency of clinker production, the implementation of carbon capture and storage (CCS) technologies, the impact of clinker substitutes and alternative binders in concrete, low carbon concrete technologies, and re-carbonation. Thirty companies from the cement and concrete sectors, have already committed to the initiative (GCCA 2021). The European Cement Association (CEMBUREAU) has publicly stated its ambition to reach carbon neutrality along the value chain by 2050 (CEMBUREAU 2020). HeidelbergCement has committed itself to reduce its specific net CO_2 emissions per ton of cement produced by 30% compared to 1990 levels by 2030 and has a vision to reach carbon neutral concrete by 2050 at the latest. This is the first cement company in the world to receive approval for science-based CO_2 reduction targets (Plaza et al. 2020).

2.2 THE CEMENT PRODUCTION PROCESS AND THE USE OF ALTERNATIVE FUELS

The main process options for cement processing may vary regarding equipment design, method of operation and type and amount of fuel consumption (Rahman et al. 2015). However, the general cement production process involves three main stages: raw materials preparation, clinker production and clinker grinding with other components to produce cement. Different raw materials (mostly limestone, clay and other minor minerals) are mixed and milled into a homogeneous powder, from which clinker is produced in high temperature kilns. The calcium oxide (CaO) together with silica (SiO_2), iron oxide (Fe_2O_3) and alumina (Al_2O_3) form the cement clinker. The kiln operates at a temperature of 1400-1500°C which is required to complete the reaction of belite with CaO to form alite (Ca_3O-SiO_4). The clinker is then cooled down to around 120°C and is ground together with gypsum and other additives to produce the cement mix. The flue gases of the kiln are directed back to the pre-calciner, in order to preheat the homogenized raw materials and raise its temperature to the desired pre-calcination level (>900°C), and finally are emitted to the atmosphere (Pales and Leung 2018; Rahman et al. 2015; Vatopoulos and Tzimas 2012).

Modern technology for the cement manufacturing today compromises the use of a rotary kiln together with multi-stage cyclone preheater system and a calciner (Mikulčić et al. 2016). About 1.3-1.6 kg of raw materials are used to produce one kg of clinker, depending on the characteristics of the raw materials. The desired high temperatures in the cement kiln are achieved by the combustion of fossil or alternative fuels, therefore the CO_2 emissions of the kiln depend of the fuel type used. The most efficient kilns consume about 2.5-3.5 GJ of fuel energy per ton of clinker. Electricity is mostly used for grinding processes and the consumption ranges from 70 to 113 kWh per ton clinker. The range of values highlights the variability of the cement production processes (Vatopoulos and Tzimas 2012).

Due to the high temperatures in the kiln operation, large amounts of fuels are needed for the cement production process. Although many of the cement production processes have been adjusted over the years, there is still room for improvement in energy efficiency. Generally, fossil fuels such as coal, petroleum coke and natural gas provide the thermal energy required for cement industry (Rahman et al. 2015). Therefore, shifting away from the use of fossil fuels in cement production is pointed out as one of the key measures to decarbonize the cement sector, as a wide range of alternative fuel sources can be used in cement industry (Pales and Leung 2018; Rahman et al. 2015). It is so because the cement rotary kiln is able to burn a wide range of materials due to the long residence times at high temperatures, intrinsic ability of clinker to absorb contaminants (such as heavy metals) into the clinker and the alkaline environment of the kiln (Rahman et al. 2015). However, the utilization of alternative fuels still imposes some challenges on the calciner and kiln operation because these fuels have different combustion characteristics compared to fossil fuels. Some particular concerns are the ignition characteristics and achievable temperature in the cement kiln with high shares of alternative fuels, the incomplete combustion of alternative fuels, and the condensation of minor elements such as S, Cl, Na, and K in cooler parts of the equipment (Mikulčić et al. 2016).

To avoid these issues, a mix of fossil fuels and alternative fuels is used for cement production in many parts of the world. For example, the cement industry in EU already used about 28% of alternative fuels in 2012, while Switzerland used 41% in the same year whereas the US is currently at a level around 15% (PCA 2019; Rahman et al. 2015). Materials like refuse derived fuels (RDF), waste oils, plastics, waste tyres and sewage sludge are often available as alternative fuels for the cement industry. Biomass resources and industry waste materials are identified as particularly promising alternative fuels for the cement industry (Benhelal et al. 2013; Rahman et al. 2015). RDF and other industry waste materials may include biogenic and non-biogenic shares, which would otherwise be sent to a landfill site, burnt in incinerators or improperly destroyed (Pales and Leung 2018).

2.3 BIOMASS AS ALTERNATIVE FUEL IN CEMENT INDUSTRY

Biomass and industry waste materials with high share of biogenic materials are specially interesting for the cement industry as they can help reduce the fossil CO_2 emissions from the cement process and, in combination with CCS technologies (BECCS), promote very low or even negative emissions in the cement manufacturing. However, replacing fossil fuels with cleaner alternatives like biomass resources can decrease the CO_2 emissions from fuel combustion in the cement process manufacturing will only work as long as the alternative fuel use is used in a share that can provide high enough temperature in the kiln. Although biomass replacement ratios of approximately 20% are recommended to maintain a stable combustion process and the quality of the clinker, slightly higher values have been used with very satisfactory results (Mikulčić et al. 2016).

Biomass is already one of the most important alternative fuels used in the cement industry because of its diversity and availability (Rahman et al. 2015). Wood waste and other waste from agriculture and forest processes are some of the most common types of biomass used in the industry. The European Cement Research Academy (ECRA) estimates that waste or biomass substitution could reach 30% in developing regions and 70% in developed regions by 2050 (European Cement Research Academy and Cement Sustainability Initiative 2017). The major restrictions to the use of biomass in cement manufacturing are normally linked to economic factors, the necessity of pre-treatment stages[1], and the local availability of the resources or the transport costs, which are less restrictive than technical limitations (Mikulčić et al. 2016). A key challenge also is to ensure the availability of biomass from truly sustainable sources. Currently, the sector relies largely on waste-derived biomass; however, shifting towards a majority share of alternative fuels from biomass may eventually prompt the sector to turn to more refined fuels, such as wood pellets (Preston and Lehne 2018).

[1] There is a wide variety of options through which raw biomass can be pre-treated to energy carriers particularly suited for a specific application, including - but not limited to – drying, densification, pyrolysis or gasification.

3 Integration of CCS in cement production

Even though efforts such as fossil fuel substitution, increase of process energy efficiency and clinker substitution can reduce the specific CO_2 emissions significantly, further reductions by such conventional measures are limited. Reference analyses performed by IPCC and IEA indicate that the main technologies able to achieve the substantial decarbonization of the cement sector required by the global temperature stabilization targets is carbon capture and storage, or CCS (Edenhofer 2015; Hills et al. 2016; IEA 2021; Pales and Leung 2018; Voldsund et al. 2019). CCS involves capturing the CO_2 emissions from a cement kiln, and then transporting and permanently storing these. As we noted earlier, the process emissions from calcination cannot be avoided by simply switching fuels and/or improving energy efficiency (Preston and Lehne 2018) which means that CCS is particularly important for cement producers. The cement industry has engaged in many projects to develop CCS technologies (Preston and Lehne 2018).

3.1 CCS IN CEMENT PRODUCTION: TECHNOLOGY OPTIONS

CCS technologies can be classified in pre-combustion, post-combustion and oxy-fuel combustion methods.

Pre-combustion methods in the frame of cement production are of less importance since they can only capture fuel-derived CO_2 emissions, not the larger proportion emitted by calcination. *Post-combustion* capture methods are end-of-pipe technologies, i.e., these methods are aimed to capture CO_2 from the flue gas flow. Nitrogen and CO_2 are therefore the main substances needing to be separated in this case. Post-combustion capture technologies do not require fundamental modifications of cement kilns and could be applied to existing facilities (Pales and Leung 2018). *Oxy-fuel capture* means that CO_2 can be captured, or purified, from kiln flue gases when the combustion happens under oxy-fired conditions.

The CCS technologies currently considered for the power sector, such as post-combustion capture using amine scrubbing and oxy-combustion, have been proposed for CO_2 capture in cement plants as well (Gardarsdottir et al. 2019; Plaza et al. 2020; Vatopoulos and Tzimas 2012; Voldsund et al. 2019).

Although no capture technology has reached commercial scale in the cement sector yet, much progress has been made in the last decade (Plaza et al. 2020) and some of these CCS technologies are now approaching a demonstration stage. Worth mentioning here is the HeidelbergCement CCS project in the Slite plant in Sweden and especially the Norcem CCS project in Norway where one technology - post combustion capture with amine - is about to be demonstrated.

In the following, we describe three promising post-combustion technologies (amine scrubbing, calcium looping, and membranes) and two oxy-fuel capture technology options (full and partial oxyfuel combustion) in more detail.

3.1.1 Amine scrubbing

Amine scrubbing is an end-of-pipe CCS technology that only involves the flue gas and therefore should not directly affect the cement production process. Capture rates are expected to be >90%,but some studies have examined lower rates (Liang and Li 2012; Vatopoulos and Tzimas 2012). This is the post-combustion capture technology that is most advanced in terms of the technology readiness level, as it has already reached commercial scale demonstration in coal fired power plants (Hills et al. 2016; Plaza et al. 2020) and was selected to be implemented in the Norcem plant in Brevik (Norway)following successful pilot scale trials (Bjerge and Brevik 2014; Knudsen et al. 2014).

Although specific process details would depend upon a particular plant characteristic, a generic process has three main steps: (i) flue gas pre-treatment, with SO_2, NO_x, and dust particle removal; (ii) counter current contact of pre-treated flue gas with an aqueous amine solution in an absorber column, where CO_2 reacts with the amine at 40-60°C and atmospheric pressure, producing a decarbonized gas stream that is vented to the stack; (iii) regeneration of the spent solvent in the stripper column, at 100–120 °C and 1.5–2 atm, where a high purity CO_2 stream is recovered, while lean solvent is sent back to the absorber column, closing the loop. Aqueous solutions of alkanolamines like monoethanolamine (MEA) and diethanolamine (DEA) are traditionally used because of their rapid reaction rates and low cost. The development of second generation solvents and the optimization of the technology may lead to substantial energy savings, up to 60% in the power sector (Plaza et al. 2020).

A considerable amount of additional thermal energy is required for regeneration of the sorbent used, and electricity is needed to operate the capture unit. Therefore post-combustion amine absorption will have a large effect in the energy consumption of a cement plant (Vatopoulos and Tzimas 2012). Owing to the scarcity of low-grade heat at most cement plants, it may be more attractive to capture only a proportion of the CO_2 from the plants using excess heat available after energy efficiency measures and not invest in extra thermal energy generation capacity (Bjerge and Brevik 2014; Hills et al. 2016). The main challenge for implementing this technology in the cement sector is the scale-up of the process. Also, contaminants such as SO_2, NO_2 in the flue gases can be detrimental to the operation of the scrubber unit, as they would poison the absorption solvent (Vatopoulos and Tzimas 2012). However, these contaminants can be easly handled by existing SO_x and NO_x removal technologies. For example, testing at Norcem at site with industrial flue gas with Akers solvent have been carried out before deciding to implement this CCS technology.

3.1.2 Membranes separation

Gas separation membranes are based in physical and chemical interactions between the different gas components and the membrane material: one component passes through the membrane faster than another, being separated by the pressure gradient and the different diffusivities of the molecules (Plaza et al. 2020). Using membranes as a CO_2 separation technique could theoretically produce a yield of more than 80%. The higher concentration of CO_2 in cement flue gas compared to other sources is advantageous for all separation technologies, and especially for membranes, because of the larger partial pressure driving force. However, membranes have only been proven on small or laboratory scales where up to 60-70% recovery yields were achieved (Pales and Leung 2018; Plaza et al. 2020). Membrane systems do not require regeneration and their overall energy demand may be lower than competing technologies. However, membranes require pressurized or vacuum conditions for operation, which also imply in additional energy demand (Pales and Leung 2018). Membrane systems can be sensitive to sulphur compounds and other potential contaminants, and in some cases, to high temperatures. It is therefore important the selection of the optimal combination of gas cleaning technologies and membrane material. Another option being investigated is the combination of a single-membrane separation unit for bulk separation with a CO_2 liquefaction train from which the waste stream is recycled and mixed with the feed to the membrane system. This combination would enable both systems to operate in their optimal ranges in terms of CO_2 concentration (Bouma et al. 2017; Pales and Leung 2018). An example of test of membranes technology in the cement industry is within the MemCCC project in the Norcem's cement plant, Brevik, Norway (Plaza et al. 2020).

3.1.3 Calcium looping

Calcium looping (CL) is a high temperature CO_2 capture technology that separates the CO_2 contained in flue gases from sorbents based on calcium oxide through sequential carbonation-calcination cycles (Romano et al. 2013). A regenerable CaO sorbent (usually derived from limestone) is repeatedly cycled between the two vessels. In one vessel (the carbonator) carbonation of CaO occurs, and CO_2 is captured in a circulating fluidized bed carbonator operating between 600-700°C (Romano et al. 2013; Vatopoulos and Tzimas 2012). The solids stream (mainly $CaCO_3$ formed and nonreacted CaO) goes to the calciner, where in an atmosphere of O_2/CO_2 at temperatures over 900°C the $CaCO_3$ decomposes into CaO which is recycled in the carbonator and a CO_2 concentrated stream. In order to achieve a CO_2 composition suitable for storage (>95% CO_2) this calciner operates with pure oxygen. Therefore, CL installation always requires the integration with a process for producing pure oxygen. High reactivity of the CaO used is kept by continuously replacing part of the non-reactive CaO. The SO_2 produced in the kiln due to fuel combustion is also captured, as it reacts with CaO to form $CaSO_4$ (sulphation reaction) (Vatopoulos and Tzimas 2012). CL utilizes technologies that have been demonstrated at large scale and it can be implemented with a very tight integration with the cement process, as studied in the CEMCAP[2] and CLEANKER[3] projects There are some reported independent projects in order to scale-up CL technology, including pilot plant trials with CO_2 capture such as the demonstration of the entrained flow CL technology at TRL 7 through the design, construction and operation of a pilot system in the Buzzi Unicem's cement plant in Vernasca, Italy (CLEANKER project) and demonstration installation of 200 kWth at Stuttgart University. Larger scale demonstrations are also planned and have indicated CO_2 capture efficiency levels of 80-90% (Dean et al. 2011; Plaza et al. 2020).

3.1.4 Oxy-fuel technologies

Oxy-fuel combustion stands as a promising carbon capture technology as it improves fuel efficiency and provides a relatively low-cost option for CO_2 abatement in cement plants compared to other technologies. Since the early 2000s, oxy-fuel has been promoted as a CCS technology that could achieve a high capture efficiency at lower cost than alternative post-combustion processes (Carrasco-Maldonado et al. 2016; Plaza et al. 2020). The technology is based on combustion of the fuel in an atmosphere of oxygen and recirculated flue gas (mainly CO_2) instead of air. The flue gases are then ideally composed of only water vapour and CO_2, which are easily and cheaply separated by condensation. This is in contrast to conventional combustion with a post-treatment capture scheme, where CO_2 is only a minor component of the flue gases and which means that energetically intensive chemical separation is required (Ditaranto and Bakken 2019). The oxygen boosted combustion in the cement kiln leads to reduced nitrogen content that does not have to be heated up. This energy can instead be used for the calcination process, which can lead to the reduction of flue gas volume or to an increase of kiln capacity. However, this is limited to 23-50% since there is a maximum acceptable concentration of oxygen (30-35% by volume) to avoid excessive damage to the cement kiln and to manage NO_x emissions due to increasing thermal NO_x formation (ECRA 2009; Vatopoulos and Tzimas 2012). In oxy-fuel combustion, flue gas recirculation is essential to control the temperature in the kiln and to provide suitable gas velocities to the cement process (Carrasco-Maldonado et al. 2016). The integration of this technology in existing cement plants is relatively complex since it is highly integrated with the production process (Gardarsdottir et al. 2019; Voldsund et al. 2019). The disadvantage and energy penalty in the oxy-fuel capture technology is the need to produce high purity oxygen (95%) in an Air Separation Unit (ASU). The technology may also require adaptation of the combustion equipment as moving the oxidizer composition from air has significant impact on the characteristics of the flame developed in the rotary kiln by affecting many combustion properties. Besides it is important that the heat transfer to the clinker remains the same to maintain product quality and process efficiency (Carrasco-Maldonado et al. 2016).

The CO_2 concentration in the kiln preheater and pre-calciner rises from 20%-30% in a conventional process to over 80% when oxy-combustion is applied, with the rest of the gas consisting of air leak in N_2, O_2, and traces of NO_2, SO_2 and Ar. This has a major effect on the energy balance as well as the ratio between the energy content of the kiln flue gases and the energy needed for the chemical reactions of the kiln feed. Hence, the recirculation rate is used to control the combustion temperature. The largest issue is the partial pressure of CO_2 which affects the reaction type. At a low partial CO_2 pressure, $CaCO_3$ decomposition increases until reaction completion. Under high partial CO_2 pressures, there is no reaction until a minimum threshold temperature is reached. If the temperature drops below that critical point, CaO promptly returns to $CaCO_3$ through the carbonation reaction (inverse calcination) (Plaza et al. 2020; Vatopoulos and Tzimas 2012).

To integrate the oxy-combustion technology into the clinker making process, an oxygen supply facility (ASU) and a CO_2 purification unit (to enrich the CO_2 stream and allow its transport and storage) are required. Both

[2] https://www.sintef.no/projectweb/cemcap/

[3] www.cleanker.eu

these plant components significantly influence the energy consumption. Research efforts focus on energy saving in oxygen separation, with chemical looping technology currently under development and cryogenic air separation the most energy efficient technology for oxygen production, with a power consumption of 200-240 kWh per ton oxygen (ECRA 2009), although developments have reported a reduction in the energy requirement to around 160 kWh per ton oxygen (Vatopoulos and Tzimas 2012).

Oxy-fuel capture technologies can be differentiated by the extent to which oxy-firing is applied in the cement kiln. Partial oxy-fuel consists of the application of oxy-combustion at the pre calciner stage only. Full oxy-fuel also includes oxy-fuel in the firing of the cement kiln. While CO_2 separation yields for the partial option are reported in the range 55-75%, full oxy-fuel can theoretically reach 90-99%. Even if these technologies do not necessarily incur additional fuel consumption, their use requires re-engineering the plant to optimize the heat recovery system and minimize air ingress. The oxygen provision also needs to be satisfied through onsite generation or imports of electricity. Due to a different process layout compared to power industry as well as different boundary conditions, further investigations and demonstration activities are required to develop the oxy-fuel cement process to maturity (Carrasco-Maldonado et al. 2016). The oxy-fuel capture technology has raised particular focus when the European Cement Research Academy (ECRA) announced in 2018 that the technology would be demonstrated at industrial scale in two cement plants in Europe in the HeidelbergCement plant in Coleferro (Italy) and Lafarge Holcim plant in Retznei (Austria) (Ditaranto and Bakken 2019; Plaza et al. 2020). However, it is not clear if these demonstration plans are still under consideration.

Another important feature of the CCS using oxy-fuel technologies is the fact that the oxy-fuel combustion conditions may allow the use of higher shares (>20%) of biomass as alternative fuel, as the temperature control of the kiln process operation is made by the recalculation of flue gases. Although the burner technology for oxyfuel combustion has been the matter of several research and development projects from lab-scale up to large-scale pilot facilities in the power sector (Plaza et al. 2020) and the physics of combustion in a high CO_2 atmosphere are mainly understood (Ditaranto and Bakken 2019), the application of this technology in the clinker burning process carries new uncertainties in particular regarding the use of high shares of alternative fuels, including biomass and industry residues with high shares of biogenic carbon. These aspects are currently under study by the AC2OCem project (AC2OCEM 2021). The successful combination of oxy-fuel CCS technologies with the high shares of biomass use as alternative fuel will lead to a proper BECCS set up for cement industry that may achieve very low or even negative emissions in the cement production process.

Table 1 summarizes the key CCS technologies tested for cement production in recent years as well as some advantages and disadvantages related to them. The following sections provide more details regarding how each technology work, energy demands and emission reduction potentials.

Table 1: Comparison of CCS technologies for cement production. Based on (Carrasco-Maldonado et al. 2016; Gardarsdottir et al. 2019; Hills et al. 2016; Koring et al. 2013; Plaza et al. 2020; Rodríguez et al. 2012; Schakel et al. 2018; Voldsund et al. 2019).

Attribute	Amine scrubbing	Membrane separation	Calcium looping	Partial oxy-fuel	Full oxy-fuel
Advantages	Maturity of technology. High capture efficiency. Regeneration of solvent possible.	Process has been adopted for separation of other gases. High separation efficiency achievable. No additional thermal energy demand.	Low energy efficiency loss. Highly promising technology for cement industry due to heat recovery.	Lower additional thermal demand. Retrofitting is feasible.	No additional thermal demand. High capture efficiency.
Challenges	High thermal energy demand for solvent regeneration. Cost of solvent. Equipment corrosion. Solvent degradation.	Influence of minor components (i.e. water, SO_2) on gas permeation performance. High cost and high energy demand for compression equipment. Limited CO_2 purity. High membrane area demand for large facilities.	Attrition depending on raw meal/limestone hardness.	Higher electricity demand for ASU and CPU. High effort for sealings necessary.	Higher electricity demand for ASU and CPU. High effort for sealings necessary Complex retrofitting in core process which yields additional risks
Complexity	Low: mature end-of-pipe technology, but extensive flue gas cleanup is required before capture.	Low: although the technology not proven at necessary scale	Medium: integration should be simple but fluidized bed combustor operation is outside cement industry knowledge.	Medium: increased design and maintenance complexity (although less than full oxyfuel); operation of the plant should be relatively similar to unabated cement.	High: increased design and maintenance complexity; operation of the plant changes, especially in kiln and cooler. Kiln stop likely if O_2 supply fails.
Major changes to cement process	None	None	Precalciner replaced with dual fluidized beds steam cycle, and associated equipment.	New preheaters and precalciner necessary.	New preheaters and precalciner necessary. Changes to kiln burner and cooler designs necessary. False air-flow reduction requires altered designs of units
Typical CO_2 capture rate	>90%	>80%	>90%	65%	>90%
Capital cost (€)	440–540 M for 1 Mtpa New built 245–350 M for 1 Mtpa Retrofitted		125 M New built (capture plant only) for 1 Mtpa	85 – 107 M for 1 Mtpa Retrofitted 275 M for 1 Mtpa New built	291 M for 1 Mtpa New built 104 M for 1 Mtpa Retrofitted
Overall cost, avoided (€/ t CO2)	107 New built 143–187 Retrofitted	47-48	75–85 Retrofitted 18-31 new built	54–69 Retrofitted 12 New built	39 New built 41 Retrofitted
Possibility to use biomass & other alternative fuels	Unaltered, as it is a post combustion CCS option.	Unaltered, as it is a post combustion CCS option.	Use of biomass improves efficiencies compared to coal, thanks to lower ash & sulphur contents	The oxyfuel conditions in the preheater and calciner stages would allow higher shares of alternative fuels than in conventional processes.	New oxyfuel kiln burner concepts may allow the use of up to 100% of biomass and other alternative fuels. However, this is still in the development stage.

3.2 EXAMPLE OF CCS IMPLEMENTATION IN THE CEMENT SECTOR

Norcem AS (Norcem) is part of the HeidelbergCement Group and it is the only cement manufacturer in Norway, accounting for about 2.5% of the national emissions. The Norcem plant in Brevik is part of Europe's first industrial demonstration of CO_2 capture, transport and storage and the world's first CO_2-capture facility at a cement factory. The captured CO_2 will be liquefied and temporarily stored at Brevik facilities, and then shipped to an onshore terminal at Øyrgarden, on the Norwegian west coast, from where it will be transported and injected into a CO_2 storage site offshore Norway, developed by the Equinor-headed Northern Lights consortium. An essential element in the planned carbon capture is to make use of the residual heat from the cement factory. There is enough residual heat to capture approximately 400,000 tons of CO_2 annually, which corresponds to about 50% of the plant's emissions. The project is using a post combustion technology based on amine capture, so called Aker Solutions' Advanced Carbon Capture technology and its S26 amine solvent (Plaza et al. 2020). This technology was selected following successful chemical absorption trials using amine-based sorbents (Bjerge and Brevik 2014; Knudsen et al. 2014). A specific learning element from Norcem is how the capture plant will be designed to capture an optimal amount of CO_2 through the use of the surplus heat from the production of cement. This can be transferred to the process industry in general, since this industry often has surplus heat that can be used. The total cost (investment and operating costs for five years) for a chain where CO_2 from Norcem is captured and stored is estimated at about 1.3 billion Euros. The Norwegian Parliament has recently voted in favor of the government's proposed grant of funding for the project. The project is expected to initiate operations in 2023 (Plaza et al. 2020).

4 Discussion and policy recommendations

4.1 CCS AS AN OPTION FOR DECARBONISATION OF HEAVY INDUSTRY

The last five-year period has seen a substantial increase in the research, innovation and policy space around different strategies that can enable close-to-zero emissions in heavy industry sectors like steel, chemicals and cement. Contrary to what earlier was conventional wisdom, it has become increasingly clear that for most applications within these so-called hard-to-abate sectors, there are technological options that could be implemented at relatively modest costs. From a broad perspective, the solution set can be grouped into two categories, the first based on adapting existing processes through fuel-switching and/or adding CCS (also considering that more substantial retrofitting in core equipment would be required for the oxyfuel CCS process) and the second based on more radical changes whereby new processes are introduced, typically based on electrification or hydrogen (Bataille et al. 2018).

As we have noted in this report, it will in all likelihood be impossible to reach deep emissions reductions in the cement sector without CCS and there are several different technological options available by which CCS can be implemented. Their characteristics vary when it comes to operational aspects and level of investments needed, but one thing that they do have in common is that it is inevitable that even with cost reductions that come with increasing technological maturity, their introduction will substantially increase the production cost of cement. A key question for cement decarbonization is thus how these costs should be covered.

Another important question is if the combination of increased use of biomass as alternative fuel in cement plants in combination with CCS technologies could lead to net negative emissions in the cement sector. A recent study addressing the carbon capture and biomass in industry shows that the substitution of 50% (in energy) of fossil fuel with biomass, in combination to use of CCS technologies, may lead to very low (but still positive) net carbon emission from the cement production process (Yang et al. 2021). This maximum substitution rate of 50% for biomass is linked to technical limitations, such as required fuel properties and thermal energy rate supply. However, negative emissions can still be achieved in the cement production process with the combination of increased use of biomass with the use of other alternative fuels with relatively high biogenic share (e.g., some types of RDF, sewage sludge) to maximize the substitution of fossil fuels in the process, tackling the technical limitations of biomass use only.

4.2 HOW TO INCENTIVIZE CCS IN THE CEMENT SECTOR?

As a first-of-a-kind project, the Norwegian Langskip initiative, which includes CCS deployment at the Norcem plant, will receive project-specific funding for both capital and operational expenses. With the aim to demonstrate not only the CO_2 capture at the cement production but the full CCS supply chain, the Norwegian government will cover a substantial share of capital and operational expenses, the latter over a time period of 10 years. However, long-term broad deployment across the cement sector globally necessitates broader policy measures. Here we review a couple of these that might be of particular relevance for deployment of CCS in the cement sector.

Carbon pricing is often seen as an effective and efficient instrument to incentivize companies to reduce their emissions, but actual implementation tends to be difficult, especially so in the industrial sectors. Notably, in the EU Emissions Trading System (ETS), heavy industry sectors receive free allocation of EU Allowances (EUAs). This is on the grounds that unlike the power & heat sectors, industrial products can be traded globally which means that producers are exposed to competition from non-EU producers. Consequently, there is a risk of “carbon leakage”, i.e., that EU producers would be at a competitive disadvantage compared to non-EU producers that are not obliged to buy EUAs.

When it comes to cement specifically, there has been ongoing discussions pertaining to whether or not EU cement producers actually are at risk of carbon leakage. The reason why this is up for discussion is a combination of *a)* that EUA prices for quite some time were quite low and *b)* that the low value-to-weight ratio of cement means that transport costs have been too high for most non-EU cement to be competitive on EU markets (Nykvist et al. 2020)[4]. However, a CO_2 price high enough to make CCS implementation economically viable is also likely to make it possible for non-EU cement producers to compete in EU markets, with ensuing risks of carbon leakage (Material Economics 2019). One way to get around this issue is to introduce a so-called carbon border adjustment mechanism (CBAM) whereby a tariff would be added to imported cement with poorer greenhouse gas emission profile. There is currently a lot of discussion both around the merits and drawbacks of CBAMs as well as around the practicalities pertaining to how they could be implemented.

Another policy tool that could be used to incentivize cement producers to implement bio-CCS, as well as other drastic emission reductions, is to take more of a full value chain approach. As has been shown by e.g., Rootzén & Johnsson (2017), implementing measures that enable close-to-zero emissions from cement production will entail substantial increases in the cost of the cement, but the effect on the cost of a building constructed using such zero-emission cement can be less than 1%. This opens the door for the introduction of policies that are aimed not at the cement producers as such but at downstream buyers. These could be in the form of mandates that require buildings and infrastructure to be constructed only using cement that has a very low GHG footprint.

For cement, a considerable share of market volumes is purchased under public procurement regulation[5]. This means that there could be opportunities to use public procurement as an instrument to create the economic conditions required for installation of CCS to be a bankable investment for cement producers. Recently, Cementa - Heidelberg Cement's Swedish branch – announced that it plans to set up a CCS supply chain where CO_2 generated at its facility in Slite, Gotland would be captured and stored. Cementa plans to combine the implementation of CCS with a growing use of biomass-based fuels and argue that this will enable the production of CO_2-negative cement. In contrast to the Norcem/Langskip project, it seems Cementa's plans will not be based on direct governmental funding for the specific project but more likely on the introduction of guidelines that mandate public procurers to only buy cement and derived products with close-to-zero CO_2 emissions (Cementa 2021). The exact design and implementation of these guidelines are still under development and to be effective on the longer term, they would need to be standardized beyond national borders.

4.3 THE IMPORTANCE OF CARBON DIOXIDE REMOVAL POLICY DESIGN

While our focus in this report has been on the implementation of CCS in combination with the use of biomass for the provision of process heat, it is important to emphasize that there are also approaches that combine CCS with electrification of the process heat using plasma heating. While the electrification approach is currently not ready for commercial deployment (IEA 2020), it is worthwhile to briefly discuss some conceptual aspects of these two different approaches.

An important advantage of the electrification approach is that the CO_2 stream to be captured is highly concentrated, originating only from the calcination process and not from the combustion of any fuels (Wilhelmsson et al. 2018). This could entail lower capture costs but would require large upfront investments. Low electricity prices, in addition to adequate infrastructure and grid capacity, will also be important factors (Karlsson et al. 2020). Obviously, it is also key that the electricity used is generated using low-emission technologies in order to minimize the life cycle emissions of this approach.

When it comes to the option of instead using biomass-based fuels as the source of process heat, a key advantage in addition to more mature technologies is that capture and storage of the resulting CO_2 would entail carbon dioxide removal (CDR) from the atmosphere. This could, as noted earlier, enable overall

[4] Furthermore, there may be strict quality requirements that are specific to certain countries or sectors which means that imported cement may not always be used as a direct substitute for EU cement.
[5] An example here is that one-third of cement used in Sweden is indirectly procured by the Swedish Road Administration (Pädam et al. 2021)

cement production emissions to be low or even negative, although this will depend on the life cycle emissions of the biomass feedstock in question. Regardless, this raises interesting questions that are related to how negative emissions will be regulated and if/how these frameworks will link to frameworks that govern fossil CO_2 emissions (Carton et al. 2021; Rickels et al. 2020).

4.4 ACCELERATE BOTH TECHNOLOGICAL INNOVATION AND POLICY DEVELOPMENT

In summary, it is important to emphasize that addressing these questions around policy design around deployment of CCS in the cement industry sooner rather than later. While CCS is not by itself sufficient to enable cement production aligned with global climate change mitigation ambitions, it will be a necessary tool. The thirty years remaining until 2050 – the target year in IEAs global net-zero scenario – might seem like a long time but in terms of decarbonizing the global cement industry, it is a very challenging timeline. Full CCS value chains are yet to demonstrated for the cement industry and there is still plenty of work to be done in the realms of policy design and implementation. In order to prevent further lock-in into high-emitting cement production pathways (Maltais et al. 2021), it is therefore high time to accelerate both technological development and policy innovation to ensure that upcoming reinvestments are compatible with technological pathways for steep emission reductions.

References

AC2OCEM (2021). AC2OCEM Project. http://www.act-ccs.eu/ac2ocem

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., et al. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement. *Journal of Cleaner Production*. DOI: 10.1016/j.jclepro.2018.03.107

Benhelal, E., Zahedi, G., Shamsaei, E. and Bahadori, A. (2013). Global strategies and potentials to curb CO2 emissions in cement industry. *Journal of Cleaner Production*, 51. 142–61.

Bjerge, L.-M. and Brevik, P. (2014). CO2 capture in the cement industry, norcem CO2 capture project (Norway). *Energy Procedia*, 63. 6455–63.

Bouma, R., Vercauteren, F., van Os, P., Goetheer, E., Berstad, D. and Anantharaman, R. (2017). Membrane-assisted CO2 liquefaction: performance modelling of CO2 capture from flue gas in cement production. *Energy Procedia*, 114. 72–80.

Carrasco-Maldonado, F., Spörl, R., Fleiger, K., Hoenig, V., Maier, J. and Scheffknecht, G. (2016). Oxy-fuel combustion technology for cement production–state of the art research and technology development. *International Journal of Greenhouse Gas Control*, 45. 189–99.

Carton, W., Lund, J. F. and Dooley, K. (2021). Undoing equivalence: Rethinking carbon accounting for just carbon removal. *Frontiers in Climate*, 3. DOI: 10.3389/fclim.2021.664130

CEMBUREAU (2020). *Cementing the European Green Deal, The European Cement Association*Brussels, Belgium, 2020.

Cementa (2021). *Sweden First in the World with Carbon-Neutral Cement Plant*. https://www.cementa.se/sv/sweden-first-in-the-world-with-carbon-neutral-cement-plant

Dean, C. C., Dugwell, D. and Fennell, P. S. (2011). Investigation into potential synergy between power generation, cement manufacture and CO 2 abatement using the calcium looping cycle. *Energy & Environmental Science*, 4(6). 2050–53.

Ditaranto, M. and Bakken, J. (2019). Study of a full scale oxy-fuel cement rotary kiln. *International Journal of Greenhouse Gas Control*, 83. 166–75.

ECRA (2009). *European Cement Research Academy, CCS Project e Report about Phase II. Technical Report TR ECRA-106/2009.*

Edenhofer et al. (2015). *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press

European Cement Research Academy and Cement Sustainability Initiative (2017). Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead. , 2017.

Gardarsdottir, S. O., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., et al. (2019). Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. *Energies*, 12(3). 542. DOI: 10.3390/en12030542

GCCA (2021). Innovandi—The Global Cement and Concrete Research Network.

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A. and Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, 1(11). 559–73. DOI: 10.1038/s43017-020-0093-3

Hills, T., Leeson, D., Florin, N. and Fennell, P. (2016). Carbon capture in the cement industry: technologies, progress, and retrofitting. *Environmental Science & Technology*, 50(1). 368–77.

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

IEA (2021). *Net Zero by 2050 - a Roadmap for the Energy Sector*. https://www.iea.org/reports/net-zero-by-2050

Karlsson, I., Toktarova, A., Rootzén, J. and Odenberger, M. (2020). *Technical Roadmap: Cement Industry*. Mistra Carbon Exit. https://www.mistracarbonexit.com/s/MistraCarbonExit_Roadmap_Cement_v4.pdf

Knudsen, J. N., Bade, O. M., Askestad, I., Gorset, O. and Mejdell, T. (2014). Pilot plant demonstration of CO2 capture from cement plant with advanced amine technology. *Energy Procedia*, 63. 6464–75.

Koring, K., Hoenig, V., Hoppe, H., Horsh, J., Suchak, C., Llevenz, V. and Emberger, B. (2013). Deployment of CCS in the Cement Industry. *IEA Report 2013*, 19.

Liang, X. and Li, J. (2012). Assessing the value of retrofitting cement plants for carbon capture: A case study of a cement plant in Guangdong, China. *Energy Conversion and Management*, 64. 454–65.

Maltais, A., Gardner, T., Godar, J., Lazarus, M., Mete, G. and Olsson, O. (2021). What does it take to achieve net zero? Opportunities and barriers in the steel, cement, agriculture, and oil and gas sectors. https://www.sei.org/publications/what-achieve-net-zero/

Material Economics (2019). *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry*

Mikulčić, H., Klemeš, J. J., Vujanović, M., Urbaniec, K. and Duić, N. (2016). Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process. *Journal of Cleaner Production*, 136. 119–32.

Nykvist, B., Maltais, A. and Olsson, O. (2020). *Financing Decarbonisation of Hard-to-Abate Sectors in Sweden)*. Stockholm Sustainable Finance Centre/SEI

Pädam, S., Balian, D., Uppenberg, S. and Wadström, E. (2021). *Klimatneutral Betong Genom Kravställning*. Swedish Environmental Protection Agency. https://www.naturvardsverket.se/Documents/publ-filer/6900/978-91-620-6967-4.pdf?pid=28150

Pales, A. F. and Leung, Y. (2018). Technology Roadmap-Low-Carbon Transition in the Cement Industry. 2018. *International Energy Agency:*

PCA (2019). *Energy & Environment Priorities*. US Portland Cement Association. https://www.cement.org/issues-advocacy/legislative-priorities/energy-environment-priorities

Plaza, M. G., Martínez, S. and Rubiera, F. (2020). CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations. *Energies*, 13(21). 5692.

Preston, F. and Lehne, J. (2018). Making Concrete Change Innovation in Low-carbon Cement and Concrete.

Rahman, A., Rasul, M. G., Khan, M. M. K. and Sharma, S. (2015). Recent development on the uses of alternative fuels in cement manufacturing process. *Fuel*, 145. 84–99.

Rickels, W., Proelss, A., Geden, O., Burhenne, J. and Fridahl, M. (2020). *The Future of (Negative) Emissions Trading in the European Union*. DOI: 10.13140/RG.2.2.21635.53281

Rodríguez, N., Murillo, R. and Abanades, J. C. (2012). CO2 capture from cement plants using oxyfired precalcination and/or calcium looping. *Environmental Science & Technology*, 46(4). 2460–66.

Rolfe, A., Huang, Y., Haaf, M., Pita, A., Rezvani, S., Dave, A. and Hewitt, N. J. (2018). Technical and environmental study of calcium carbonate looping versus oxy-fuel options for low CO2 emission cement plants. *International Journal of Greenhouse Gas Control*, 75. 85–97.

Romano, M. C., Spinelli, M., Campanari, S., Consonni, S., Cinti, G., Marchi, M. and Borgarello, E. (2013). The calcium looping process for low CO2 emission cement and power. *Energy Procedia*, 37. 7091–99.

Rootzén, J. and Johnsson, F. (2017). Managing the costs of CO2 abatement in the cement industry. *Climate Policy*, 17(6). 781–800. DOI: 10.1080/14693062.2016.1191007

Schakel, W., Hung, C. R., Tokheim, L.-A., Strømman, A. H., Worrell, E. and Ramírez, A. (2018). Impact of fuel selection on the environmental performance of post-combustion calcium looping applied to a cement plant. *Applied Energy*, 210. 75–87. DOI: 10.1016/j.apenergy.2017.10.123

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'agosto, M., et al. (2014). *Chapter 8: Transport*. IPCC

Vatopoulos, K. and Tzimas, E. (2012). Assessment of CO2 capture technologies in cement manufacturing process. *Journal of Cleaner Production*, 32. 251–61.

Voldsund, M., Gardarsdottir, S. O., De Lena, E., Pérez-Calvo, J.-F., Jamali, A., et al. (2019). Comparison of technologies for CO2 capture from cement production—Part 1: Technical evaluation. *Energies*, 12(3). 559.

Wilhelmsson, B., Kollberg, C., Larsson, J., Eriksson, J. and Eriksson, M. (2018). *CemZero - A Feasibility Study Evaluating Ways to Reach Sustainable Cement Production via the Use of Electricity*

Yang, F., Meerman, J. C. and Faaij, A. P. C. (2021). Carbon capture and biomass in industry: A techno-economic analysis and comparison of negative emission options. *Renewable and Sustainable Energy Reviews*, 144. 111028.

IEA Bioenergy

Technology Collaboration Programme