CEMCAP

Co-funded by the European Union

Grant Agreement Number:
641185

Action acronym:
CEMCAP

Action full title:
CO_2 capture from cement production

Type of action:

H2020-LCE-2014-2015/H2020-LCE-2014-1

Starting date of the action: 2015-05-01
Duration: 42 months

D2.11
CEMCAP Strategic conclusions – progressing CO_2 capture from cement towards demonstration
Revision 1

Due delivery date: 2018-10-31
Actual delivery date: 2019-02-15

Organization name of lead participant for this deliverable:
SINTEF Energi AS

Project co-funded by the European Commission within Horizon2020		
Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Deliverable number:	D2.11
Deliverable title:	CEMCAP Strategic conclusions – progressing CO_2 capture from cement towards demonstration
Work package:	WP2 WP Dissemination and exploitation
Lead participant:	SINTEF-ER

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Keywords

CCS, CO_2 capture, cement, industry, CO_2 utilization, CCUS, techno-economic comparison, retrofitability, technology gaps, innovation

Abstract

The objective of the 42-month Horizon2020 project CEMCAP (Budget ~10 MEUR) has been *to prepare the ground for large-scale implementation of CO_2 capture in the European cement industry*. CEMCAP has tested and analyzed five different CO_2 capture technologies for cement production and performed techno-economic and retrofitability analyses. The investigated technologies are ready for or already progressing towards demonstration beyond CEMCAP. CEMCAP has thus created technology pathways for future large-scale CCS implementation in the cement industry, but these pathways need support by an appropriate political framework, business models, a reliable CO_2 transport and storage infrastructure and public acceptance for CCS.

Please cite this report as: K. Jordal, C. Abanades, G. Cinti, D. Berstad, V. Hoenig, M. Hornberger, Monteiro, J.G., Gardarsdottir, S., Ruppert, J., Størset, S., Sutter, D., van der Meer, R., Voldsund, M. *2019, CEMCAP Deliverable D2.11*. Refer to the CEMCAP community in Zenodo.org for citation with DOI.

This project has received funding from the European Union's Horizon2020 Research and Innovation Programme under Grant Agreement No 641185. This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 15.0160

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EXECUTIVE SUMMARY

In 2014, the EU set ambitious climate targets of 40% emissions reductions by 2030, compared to 1990 levels, and 80-95% reductions by 2050. Furthermore, in 2018, the IPCC special report on the impacts of global warming of 1.5 ºC above pre-industrial levels stressed the urgency of drastic cuts in greenhouse gas emissions, including that CO_2 emission from industry should be reduced with about 75-90% by 2050.

Cement production currently contributes globally with 6-7% of anthropogenic CO_2 emissions. In Europe, there is a high awareness about the needs for emission reductions in this industrial sector. Two thirds of the CO_2 emissions from cement production are process related emissions originating from the raw material limestone. Significant CO_2 reductions are therefore especially challenging. In order to meet European and global climate goals, wide-spread application of CO_2 capture and storage (CCS) technologies are a necessary part of roadmaps for significant emissions reductions and climate protection in the cement industry.

The objective of the Horizon2020-funded Research and Innovation project CEMCAP has been *to prepare the ground for large-scale implementation of CO_2 capture in the European cement industry*. The project duration has been May 2015-October 2018 (42 months). Total budget has been ~10 MEUR.

CEMCAP has in a consistent manner tested, analyzed and compared five technologies for CO_2 capture from a reference cement kiln, which were assessed and compared to amine (MEA) capture. Retrofitability of CO_2 capture has been included in the evaluation, since the lifetime and use of cement kilns normally exceed 30 years.

The CEMCAP technologies for CO_2 capture in cement plants and their envisaged next steps are

- Oxyfuel capture – is being brought forward in the ECRA CCS project, with plans for demonstration at the cement plants at Colleferro (IT) and Retznei (AT).
- Chilled Ammonia Process (CAP) – A pilot plant of 100,000 tCO_2/year has been envisioned.
- Membrane-assisted CO_2 liquefaction – on-site screening of membrane materials at a cement kiln would be the next step, together with liquefaction tests.
- Tail-end Calcium Looping – is ready for on-site testing
- Entrained-flow (integrated) Calcium Looping: Is being brought to on-site demonstration in the H2020 CLEANKER project.

Compared to the reference amine capture technology MEA, all the other technologies perform better in terms of primary energy consumption. The oxyfuel process reaches the best specific primary energy consumption for CO_2 avoided (1.63 MJ/kg_{CO2}). The retrofitability of the different capture technologies was evaluated based on qualitative key performance indicators and it was found that the post combustion technologies are easier to retrofit, while the more integrated technologies (oxyfuel and integrated calcium looping) are assessed as more challenging. Altogether, there is not one "winning" capture technology but all CEMCAP technologies have been identified as relevant options for the retrofitting of existing cement plants.

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The cost of clinker production is shown to increase by 50% to 90% when CO_2 capture is introduced. The cost of CO_2 avoided calculated in CEMCAP, excluding the cost of transport and storage, is between 42 €/t CO_2 (for the oxyfuel-based capture process) and 84 €/tCO_2 (for the membrane-based assisted liquefaction capture process), while the reference MEA-based absorption capture technology is estimated at 80 €/tCO_2. The additional cost for CO_2 transport and storage will depend on the location of the cement plant relative to the storage site. Similar transport and storage costs are expected for the different capture technologies at one site.

The optimal capture technology to retrofit in a specific kiln is expected to be case dependent, and CEMCAP results and methodology provide a basis for such evaluations. Furthermore, the optimum CO_2 capture and storage (CCS) solution will be location-dependent, i.e. depend on the availability of transport infrastructure and storage availability.

CO_2 capture and utilisation of CO_2 in products (CCU) has been identified as an element that can provide a CO_2 source for some niche products, but realistically it is a question of using less than 10% of CO_2 from a few cement kilns. Overall, CCU will always need the "S" option for storage. The degree of sustainability of a CCU chain (as opposed to the CCS alternative) is greatly dependent on the CO_2 footprint of the product being displaced by a CO_2-derived product.

In sum, all CO_2 capture technologies investigated in CEMCAP are technically feasible and ready to move forward towards on-site testing and demonstration or are already proceeding in this direction. In order to continue the development towards demonstration and availability of full-scale CCS, appropriate political framework and funding are required, as well as industrial interest and ownership, business models, and appropriate legal and regulatory frameworks. Also, it is essential to achieve public acceptance for CCS as a means to curb industrial CO_2 emissions and to protect the climate whilst preserving jobs in Europe.

Where to find more information about and results from CEMCAP

The CEMCAP website contains project presentations and posters from workshops and conferences and also recordings of the final public CEMCAP webinars: www.sintef.no/cemcap. Noteworthy are the two CEMCAP pubic workshops that were organized by consortium member ECRA (the second workshop was co-organized with H2020 project CLEANKER, www.cleanker.eu/)

A list of public CEMCAP deliverables is included in appendix **Error! Reference source not found.** of this report.

Public CEMCAP deliverables can be found in the CEMCAP community in Zenodo , as well as in CORDIS (https://zenodo.org/communities/cemcap/, https://cordis.europa.eu/project/rcn/193788_en.html).

Peer reviewed and conference papers published by the end of CEMCAP are listed in appendix E. More scientific publications based on CEMCAP research are expected to be published after the end of the rpoejct. Peer-reviewed publications are Open Access and can be found through e.g. the CEMCAP page on OpenAire.

Two films have been produced an uploaded on YouTube, one about cement production and the oxyfuel clinker cooler testing, and one providing a brief presentation about the CEMCAP project.

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1 INTRODUCTION

1.1 Global warming and the need to curb industrial CO_2 emissions

"2 °C" and "1.5 ºC" are the keywords for climate change science and policy debates. The Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) agreed at its 21st session, held in Paris in December 2015, to support these ambitious long-term targets for the global warming respect to preindustrial levels. In October 2018 the IPCC published their 15th Special Report (SR15) *"on the impacts of global warming of 1.5 ºC above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the thread of climate change, sustainable development, and efforts to eradicate poverty"* [1].

In brief, there are huge challenges linked with reaching the 2 °C target, even more so to limit anthropogenic climate warming to 1.5 ºC: global emissions of CO_2 need to level off immediately, and then fall rapidly towards full decarbonization around 2050 (see for example a recent discussion on scenarios [2,3]). The role of negative emission technologies, NET, is most prominent in 1.5 ºC scenarios. It is recognized as an essential technology element, in order to achieve long term carbon neutrality of anthropogenic activities. Biomass with CO_2 capture and storage, BECCS, or direct CO_2 capture from the atmosphere, followed by permanent storage of CO_2, DAC, are receiving increasing attention despite great concerns on their environmental and economic viability at the scales required [3]. Furthermore, and due to the long residence time of CO_2 in the atmosphere, the need to deploy NET technologies increases sharply if there is an overshoot[1] in CO_2 emissions during the next decade. Such overshoot is however quite likely in view of the current trends and country commitments for emission reductions after COP 21 and the Paris agreement.

Furthermore, the IPCC SR15 Summary for Policymakers specifies that "CO_2 emission from industry in pathways limiting global warming to 1.5ºC with no or limited overshoot are projected to be about 75-90% […] lower in 2050 relative to 2010, as compared to 50-80% for global warming of 2ºC […] In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5ºC with no or limited overshoot […]".

In this context, it is evident that there is going to be an urgency to bring towards zero the emissions from any large industrial emitter of CO_2 in a region like Europe, that claims a global leadership regarding climate change mitigation policies. In 2014, the EU set ambitions climate targets of 40% emissions reductions by 2030 and 80-95% reductions by 2050 compared to 1990 levels. The case of the cement industry is somehow unique in this regard: due to the inherent process emissions originating from the raw materials used for cement production even an ideal switch to "carbon free" energy supply would only avoid about a third of the emissions today (those that come today from fossil fuels used in cement production). Figure 1 represents the evolution of the global CO_2 process emissions from cement production in the last century, excluding any emission from the fuel or the energy used in the production of cement [4]. A small fraction of these emissions are known to be offset by the slow recarbonation of cement products in contact with the atmosphere,

[1] Temporary exceedance of a specified level

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but the estimates of these flows are still uncertain, and their impact regarding carbon balances during this century are likely to be small compared to the bulk emissions plotted in Figure 1.

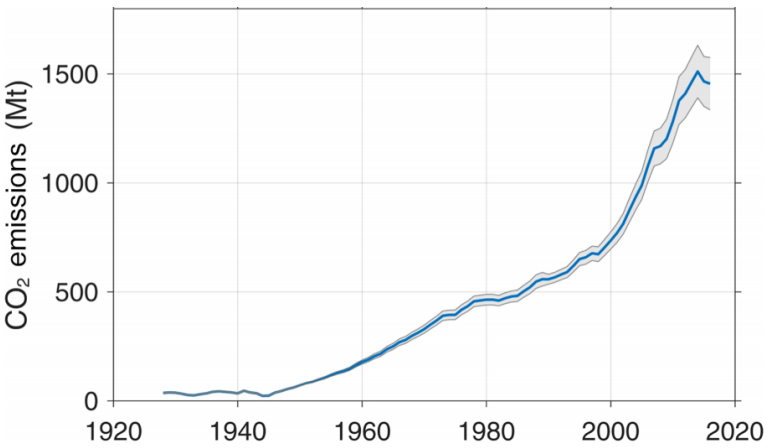

Figure 1. Global process emissions from cement production (grey bands represent 95% confidence interval). Figure reproduced from [4].

There is a limited number of options to bring to zero the process emissions from cement production. On one hand, it has long been investigated the use of non-carbonated minerals as alternative precursors of clinker. In the manufacture of pre-fabricated cement products (i.e. in a prefixed solid form) the recycling of some of the CO_2 to re-carbonate these products is gaining momentum. However, it is most likely that in order to retain the current role of cement as a durable and primary building material, the reduction of CO_2 process emissions will have to involve "CO_2 management". Two principle technological paths are considered: CO_2 capture and permanent geological storage (CCS) or CO_2 capture and utilization (CCU). Both technological paths initially require the capturing of CO_2 from the cement production process. The CEMCAP project has mainly focused on advancing technologies for CO_2 capture from cement production, but has also covered "post-capture CO_2 management". The results from the latter work are summarized in Section 4.2 of this report. A general conclusion from the CEMCAP work is that for full scale cement plants, CO_2 utilization should be considered in combination with storage (CCUS), as the amount of CO_2 likely to be utilized from a kiln is lower than 10% of the total emissions. The production of high added-values products and the displacement of CO_2-intensive raw materials may improve or even lead to positive business cases for the integrated CCUS chain. However, the possibility of having a positive business case (with no cost for CO_2 emissions in place), may be restricted to a few niche applications.

1.2 Low-carbon transition in the cement industry

With process emissions from calcination of raw materials accounting for about 2/3 of the direct CO_2 emissions from cement manufacturing, the cement industry is one of the main industrial emitters of CO_2 and globally generates around 6-7% of the total anthropogenic CO_2 emissions [5,6]. The International Energy Agency (IEA) and the Cement Sustainability Initiative (CSI) have launched a joint Technology Roadmap – Low Carbon Transition in the Cement Industry [6].

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Among the key findings and the key actions towards 2030, there are several noteworthy points which provide a context for the CEMCAP project results. This includes the very first statement in the key findings that *"Cement is used to make concrete, the most consumed manufactured substance on the planet"*, or in other words, it is difficult to imagine that the world we live in will manage without use and production of cement in the future. Rather, global cement production is set to grow by 12-23% by 2050 from the current level. It is observed that realizing the 2°C Scenario (2DS) implies a significant reduction of the global direct CO_2 emissions from cement manufacture by 24% compared to current levels by 2050, bearing in mind that there is an expected increase in global cement production. A 1.5 °C scenario is not considered in the IEA/CSI roadmap, which was launched several months before the IPCC special report referenced in Section 1.1. The main CO_2 mitigation actions mentioned in the roadmap are:

- Improving energy efficiency
- Switching to alternative fuels (fuels that are less carbon intensive and consists of waste materials partially containing biomass)
- Reducing the clinker to cement ratio
- Integrating CO_2 capture into cement production

The key indicators from the IEA/CSI technology roadmap for the cement industry in the 2DS by 2030 are provided in Table 1. It can be seen that in addition to the efficient use of clinker in cement, the use of alternative fuels and the implementation of CO_2 Capture and Storage (CCS) are the most important levers on the path to low carbon cement production.

Table 1. Key indicators in IEA/CSI technology roadmap for the global cement industry in the 2DS by 2030 [6]

	2DS low-variability case	
	2014	**2030**
Clinker to cement ratio	0.65	0.64
Thermal energy intensity of clinker (GJ/t clinker)	3.5	3.3
Electricity intensity of cement (kWh/t cement)	91	87
Alternative fuel use (% of thermal energy)	5.6	17.5
CO_2 Capture and Storage, CCS ($MtCO_2$/year)	-	14
Direct CO_2 intensity of cement (tCO_2/t cement)	0.54	0.52

The global CO_2 emissions from the cement industry in 2014 are estimated to 2.2 $GtCO_2$, which means that the 14 $MtCO_2$/year that are foreseen to be abated under the scenario outlined in Table 1 are a rather moderate share of the total CO_2 generation from the cement industry. In total, the direct CO_2 intensity of cement (which includes all the measures in Table 1) will not be much reduced from 2014 to 2030, the deep emissions reductions are foreseen to come between 2030 and 2050.

Similarly, ambitious CO_2 reduction targets have been defined by CEMBUREAU for the cement industry towards 2050 [7], specifying that a 32% emission reduction compared to 1990 can be

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achieved using conventional technologies, but in order to reduce the emissions by 80% compared to 1990, breakthrough technologies such as CCS/CCU must be applied.

CCS is a technology that has the potential to achieve deep emissions cuts in the cement industry, and it is stated in the IEA/CSI roadmap that "Immediate action is required to achieve the commercial-scale demonstration of oxyfuel carbon capture technologies in cement production by 2030, as well as to gain experience of operating large-scale post-combustion technologies in cement plants." Hence, the execution of the CEMCAP project and its objective to prepare the ground for large-scale implementation of CO_2 capture in the cement industry aligns with this identified need of IEA/CSI and CEMBUREAU. As pointed out towards the end of this report, CEMCAP has focused on technology testing and evaluation. This is necessary but not sufficient for pursuing the road towards demonstration, full-scale implementation and deployment of CCS in the cement sector. Research results were further discussed with industry and policy stakeholders in three workshops during the CEMCAP project.

1.3 About CEMCAP

The CEMCAP project was developed in response to the specific challenge with curbing industrial CO_2 emissions. The objective of this Horizon2020-funded Research and Innovation project has been *to prepare the ground for large-scale implementation of CO_2 capture in the European cement industry*. The project duration has been May 2015-October 2018 (42 months). Total budget has been ~10 MEUR, of which 8.8 MEUR was funded by the European Union.

1.3.1 CEMCAP contents

Four types of technologies for CO_2 capture from cement kilns were included in the CMECAP project: oxyfuel capture, Chilled Ammonia Process (CAP), Membrane-Assisted CO_2 liquefaction (MAL) and Calcium Looping (CaL). Furthermore, two types of CaL were investigated, tail-end CaL and integrated CaL, resulting in a total of five CO_2 capture technologies. The technologies are fundamentally different (see Section 2.1), and were selected for inclusion in CEMCAP, both due to their complementarity and due to their anticipated ability to be advanced to what is defined as TRL6 by the EU: Technology demonstrated in relevant environment[2]. Additionally, to respond to the overall project objective, the experimental research was complemented by techno-economic and retrofitability analyses of CO_2 capture from cement production. Furthermore, there has been an activity on the post-capture CO_2-management, i.e. options for handling captured CO_2.

Amine technology testing and development was not included in CEMCAP, but the well-known amine MonoEthanol Amine (MEA) was included in the techno-economic comparison as a reference technology. It is noteworthy that the CEMCAP consortium member Norcem has tested amine CO_2 capture technology on site at the cement kiln in Brevik, Norway and has now selected this technology for the Norwegian full-scale CO_2 capture project [8].

1.3.2 CEMCAP approach and overall methodology

CEMCAP has established a methodology to ensure consistency between experimental and analytical research, and between the different investigated CO_2 capture technologies. A central

[2] In CEMCAP this has mainly been understood as demonstration under conditions replicating industrial conditions, with the exception of the oxyfuel clinker cooler pilot that was tested on site at a cement kiln.

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element in this has been the collaboration on consistent specifications regarding how to do the comparative techno-economic analysis. A reference cement kiln has been defined and key performance indicators specified, together with CO_2 concentrations from the cement kiln and other information that was of relevance for ensuring consistency throughout the project. The deliverable containing this information is the CEMCAP Framework (D3.2)[3]. This report should be of relevance to consider in studies of CO_2 capture from cement production also beyond CEMCAP.

1.3.3 Expected impact from CEMCAP research

To have an impact on future CO_2 emissions reductions and contribute to curb climate change, CEMCAP has explored and expanded the options for cost- and resource-effective CCS from cement production. (Figure 2). For this to be possible, CEMCAP has built upon and united the competence and research activities on CO_2 capture within the cement industry with a wide basis of competence from more than a decade of research on CO_2 capture from the power sector. The result has been a very fruitful and effective research cooperation and an efficient use and leverage of resources through the adaptation and reuse of existing laboratory infrastructure.

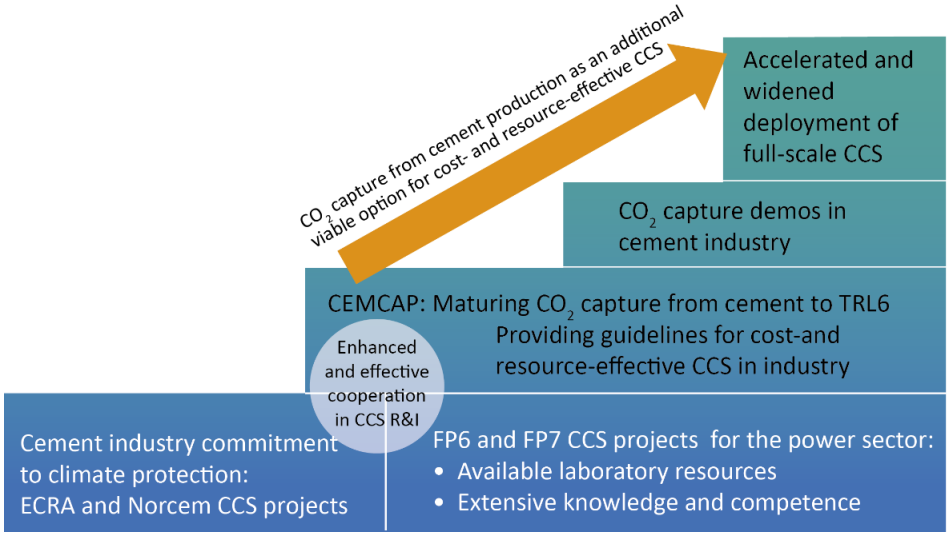

Figure 2. CEMCAP – a stepping stone towards accelerated and widened deployment of full-scale CCS.

CEMCAP leaves a heritage where five CO_2 capture technologies for cement production are ready for or already progressing towards on-site demonstration. Together with the Norcem CO_2 capture project (currently undertaking a FEED study for full-scale amine capture) and the H2020 LEILAC project (indirect calcination) [9] this provides a palette of possible CO_2 capture technologies for the cement industry. Furthermore, CEMCAP has undertaken a techno-economic comparison of these capture technologies, as well as a retrofitability analysis. CEMCAP therewith claims to have been a stepping stone towards the full-scale implementation of CCS in industry, that will be necessary to meet the 1.5 or 2 °C scenarios. But it must be recalled in this context that industrial ownership is a prerequisite for moving towards CCS demonstration, and that full-scale CCS will require a political framework, robust business models, a supporting legal framework, an established CO_2 transport and storage infrastructure and public support for CCS (see Section 5.3).

[3] CEMCAP deliverables are throughout this report referred to with their deliverable numbers. A list of CEMCAP public deliverables is provided in Appendix C of this report.

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2 TECHNO-ECONOMIC DECISION BASE FOR CO_2 CAPTURE RETROFIT

An objective in CEMCAP has been to formulate a techno-economic decision basis for CO_2 capture implementation in the cement industry. The most central documents in this decision basis are the techno-economic analysis (D4.6) with a supporting spreadsheet for in-house cost analysis and the retrofitability analysis (D4.5), and the underlying CEMCAP framework (D3.2). In a wider perspective, all of the publicly available reports from CEMCAP can be seen as part of a decision basis, for acquiring more in-depth knowledge about a specific capture technology.

This chapter presents the capture technologies investigated in CEMCAP and provides a brief overview of the results from the techno-economic comparison and retrofitability analyses, and therewith serve as an introduction to the CO_2 capture research undertaken in CEMCAP. An overview of the experimental research is provided in Appendix A.

2.1 CO_2 capture technologies for cement kilns

CEMCAP has investigated five CO_2 capture technologies for cement kilns and compared them against a reference capture technology (MEA, which is a well-known amine). The characteristics of the capture technologies are summarized in Table 2. As can be seen from the table, the technologies are fundamentally different. It should also be noted that the oxyfuel research activity has been closely linked to the ECRA CCS project [10], and that the integrated calcium looping process is now being brought to demonstration in the H2020 CLEANKER project.

2.1.1 Reference technology: MEA absorption

The reference technology MEA is a post combustion technology based on absorption (Figure 3). Flue gas from the cement kiln is first cooled in a direct contact cooler (DCC), where also SO_x is removed by scrubbing with NaOH. It is then sent to an absorber where CO_2 is absorbed by an aqueous MEA solution. MEA is recovered from the flue gas in a water wash section at the top of the absorber, and the CO_2 lean flue gas is then sent to the stack. The MEA solvent is regenerated in a desorber column, and the captured CO_2 is conditioned (compression or liquefaction) for transport. The process requires a considerable amount of heat for solvent regeneration, and power is required for fans and pumps in the MEA process, and for conditioning of the captured CO_2. Waste heat from the cement plant can be used to cover a small part of the heat demand.

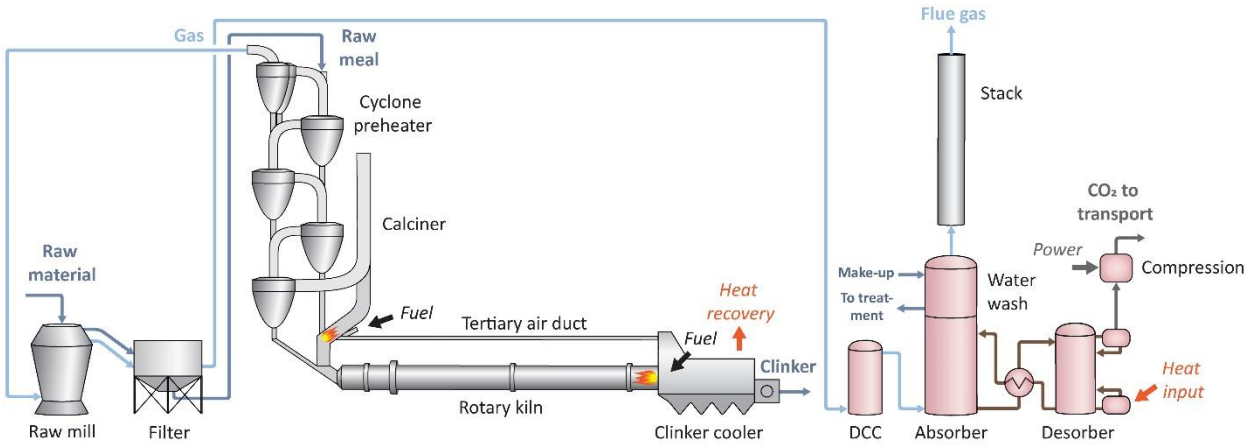

Figure 3. Reference cement kiln with MEA CO_2 absorption.

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Table 2. ***Characteristics of the different capture technologies investigated in CEMCAP.***

	Reference capture technology: MEA	**Chilled ammonia process (CAP)**	**Membrane-assisted CO_2 liquefaction**	**Calcium Looping (tail-end and integrated)**	**Oxyfuel capture**
CO_2 capture principle	Exhaust passes through a cold MEA/water mixture which absorbs CO_2, in a column. CO_2 is released as heat is added to the solution in a subsequent vessel.	Exhaust passes through a cold NH_3/water mixture, which absorbs CO_2. CO_2 is released as heat is added to the solution in a subsequent vessel.	A polymeric membrane is used to increase exhaust CO_2 concentration. CO_2 is separated through condensation after compression and cooling.	CaO particles react with CO_2 to from $CaCO_3$. CO_2 is released in a subsequent vessel through the addition of heat.	Combustion in oxygen mixed with recycled CO_2 (not air) gives a CO_2-rich exhaust.
Clinker quality	Unchanged.	Unchanged.	Unchanged.	Clinker quality is very likely to be maintained. To be verified for integrated CaL in the CLEANKER project	Oxyfuel clinker burning must be verified on plant demo scale. Oxyfuel cooling does not alter clinker quality (D9.2).
CO_2 purity and capture rate	Very high CO_2 purity. Around 90% typical capture rate.	Very high CO_2 purity. Around 90% typical capture rate.	High CO_2 purity (minor impurities present). Trade-off between capture rate and power consumption. Around 90% typical capture rate.	CO_2 purification needed (CPU). Trade-of between purity, capture rate, and power consumption. Around 90% typical capture rate.	High CO_2 purity after purification (CPU) based on very high CPU inlet initial concentration of CO_2, around 80 vol.%. Capture rate typically around 90%.
Energy demand and integration	Auxiliary low-pressure steam. Can make use of cement plant waste heat if available. Electricity required in the core process and for compression.	Auxiliary low-pressure steam required. Can make use of cement plant waste heat if available. Electricity required in core process, for chilling and compression.	Increase in power consumption, no heat integration. Electricity required for flue gas compression, vacuum pumps, and refrigeration and compression in the liquefaction system.	$CaCO_3$ regeneration requires additional fuel, which also enables low-emission electricity generation. Increased power consumption due to air separation and CPU partly supplied from heat recovery system.	Fuel demand remains unchanged. Increased power consumption due to air separation and CPU, partly supplied from waste heat recovery system.

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2.1.2 Oxyfuel capture

In the oxyfuel process (Figure 4), combustion is performed with an oxidizer consisting of oxygen mixed with recycled CO_2 to produce a CO_2 rich flue gas which allows the concentration of CO_2 to reach about 80 vol% and a relatively easy downstream purification with a CO_2 purification unit (CPU). As opposed to the post combustion capture technologies like MEA technology, the cement kiln process is modified. The gas atmosphere in the clinker cooler, the rotary kiln, the calciner and the preheater is changed, some of the flue gas is recycled, and oxygen is provided by an air separation unit (ASU). Air that is heated by hot gases from the preheater and the clinker cooler is sent to the raw mill for drying of the raw material, something that normally is done with the flue gas. Additional power is required compared to the reference kiln without capture, mainly by the ASU and by the CPU. Some of this power demand can be covered by an organic Rankine cycle (ORC) generating power from waste heat.

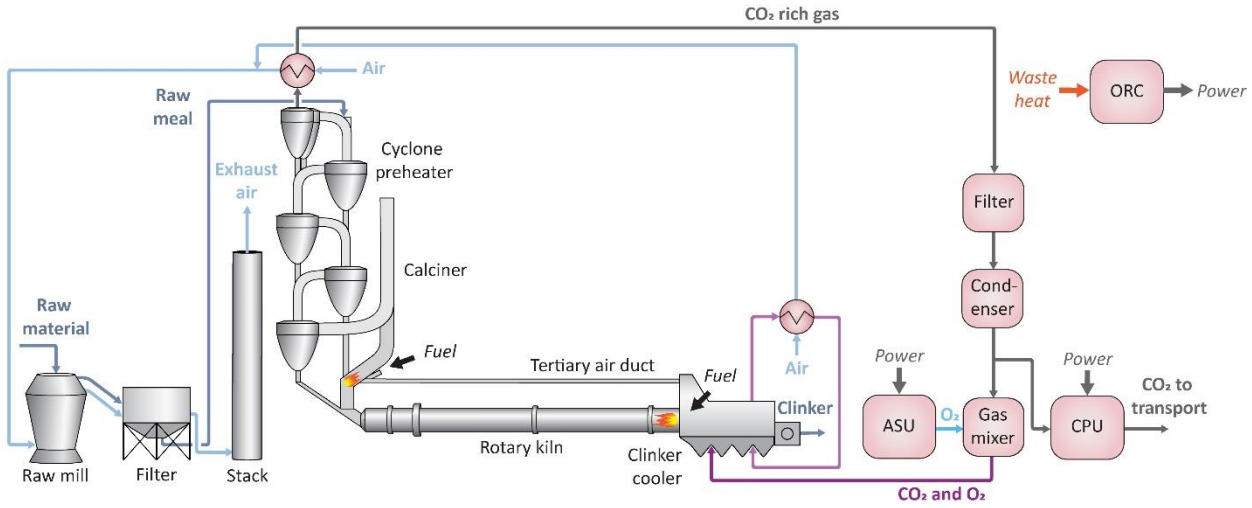

Figure 4. Reference cement kiln with oxyfuel CO_2 capture.

2.1.3 Chilled ammonia process

The chilled ammonia process (CAP) is a post-combustion technology based on absorption, where CO_2 is removed from flue gas using aqueous ammonia as solvent (Figure 5). The flue gas is first cooled in a direct contact cooler (DCC), where SO_x is removed by scrubbing with ammonia, before CO_2 is removed by a chilled ammonia solution in a CO_2 absorption column. The temperature in the absorber is controlled by a solvent pump-around that is chilled down to temperatures around 12-13°C. Ammonia is recovered from the flue gas in a water wash section at the top of the absorber, before CO_2 lean flue gas is released to the atmosphere. Ammonia is desorbed from the wash water in a desorption column and recycled into the process. CO_2 rich ammonia solvent is regenerated in a CO_2 desorber that is operated at around 20 bar. The CO_2 is conditioned to meet export specifications. In this process heat is required for solvent regeneration and for recovery of ammonia, and power is required for chilling, pumping and compression. Waste heat from the cement plant can be utilized to cover a part of the heat demand.

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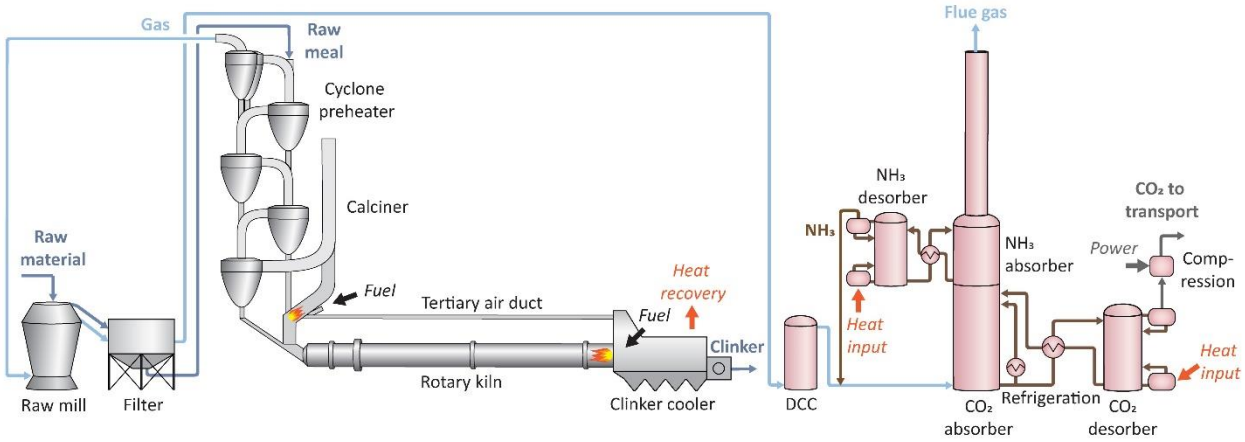

Figure 5. Reference cement kiln with CAP CO_2 capture.

2.1.4 Membrane-assisted CO_2 liquefaction

In the membrane-assisted CO_2 liquefaction (MAL) concept, polymeric membrane technology and a CO_2 liquefaction process are combined (Figure 6). Polymeric membranes are first utilised for bulk separation of CO_2 resulting in moderate product purity. This CO_2-rich product is sent to the liquefaction process, where CO_2 is liquefied, and the more volatile impurity components are removed, resulting in a high purity CO_2 product. The flue gas is first cooled, and water is removed in a DCC, and the flue gas is compressed before it is sent to the membrane module. The pressure difference over the membrane module is generated both by flue gas compression and vacuum pumps. The need for SO_x removal depends on the membrane material. In order to be conservative, it is assumed that SO_x is removed by scrubbing with NaOH in the DCC in CEMCAP. The technology is a post combustion technology with no additional integration or feedback to the cement plant, and only power is required as input to the process.

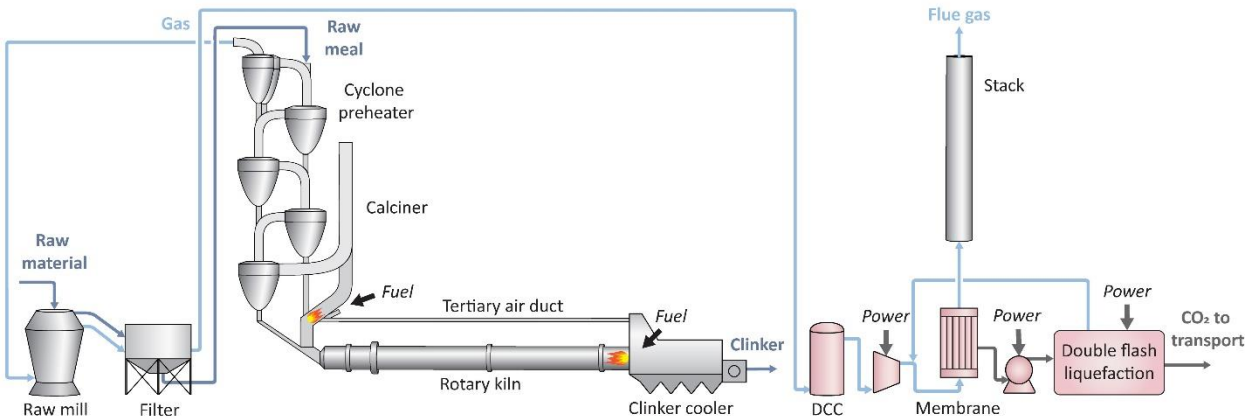

Figure 6. Reference cement kiln with membrane-assisted CO_2 liquefaction.

2.1.5 Calcium looping CO_2 capture – tail-end configuration

The calcium looping (CaL) technology is based on the reversible carbonation reaction ($CaO + CO_2 \rightleftharpoons CaCO_3$), which is exploited to separate carbon dioxide from flue gas. The technology can be applied to a cement plant as a tail-end technology (Figure 7) or it can be integrated with the calcination process taking place in the cement plant's pre-calciner (Figure 8). In the tail-end

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configuration the flue gas from the preheater tower is sent to a carbonator, where CO_2 is removed by reaction with the CaO-based sorbent. The sorbent is regenerated in a calciner, where a fuel (e.g. coal) is combusted to reach the calcination temperature of around 920 °C. The fuel combustion is performed with purified oxygen provided by an ASU to avoid dilution of the resulting CO_2 stream. The captured CO_2 needs some additional purification in a CPU. CaO-rich purge from the CaL system is sent to the cement kiln and used as raw meal. The CaL process requires supply of limestone, fuel, and oxygen. Power is required both for the core CaL process, the ASU, and the CPU. A steam cycle recovers high temperature waste heat and produces power that can be used to cover the power demand in the process and can be exported.

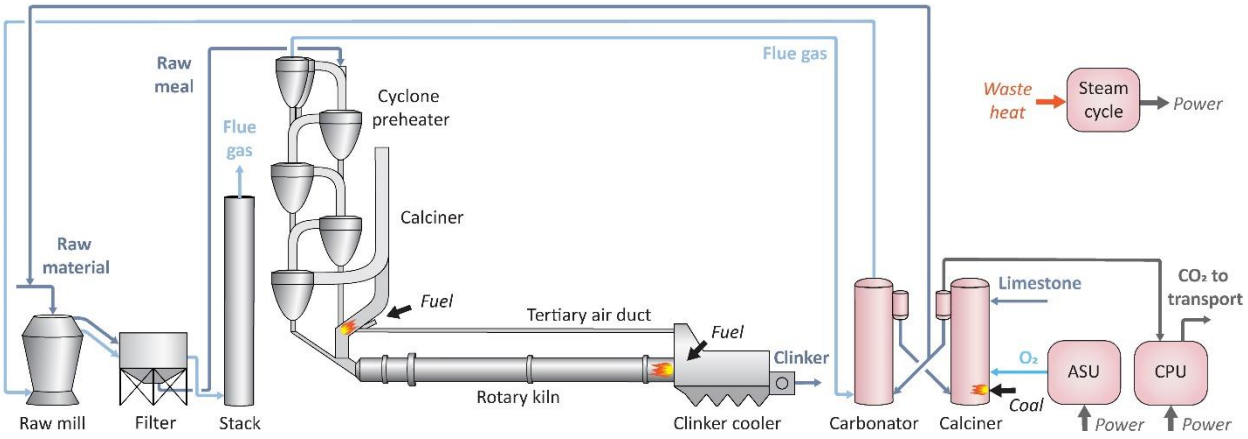

Figure 7. Reference cement kiln with calcium looping CO_2 capture – tail-end configuration.

2.1.6 Calcium looping CO_2 capture – integrated entrained flow (EF) configuration

In the integrated EF CaL configuration, the CO_2 capture calciner is combined with the cement plants pre-calciner (Figure 8), for a more energy efficient process. CO_2 from the kiln flue gas is captured in the carbonator and CO_2 form the raw meal calcination is captured in the oxfuel calciner. As a result, the carbonation and calcination must take place in EF reactors. Some additional fuel is required for operation of the calciner, and it must be operated under oxyfuel conditions. Power is required for an ASU, a CPU and in the core CaL process, but power is also generated by a steam cycle utilizing waste heat in the process.

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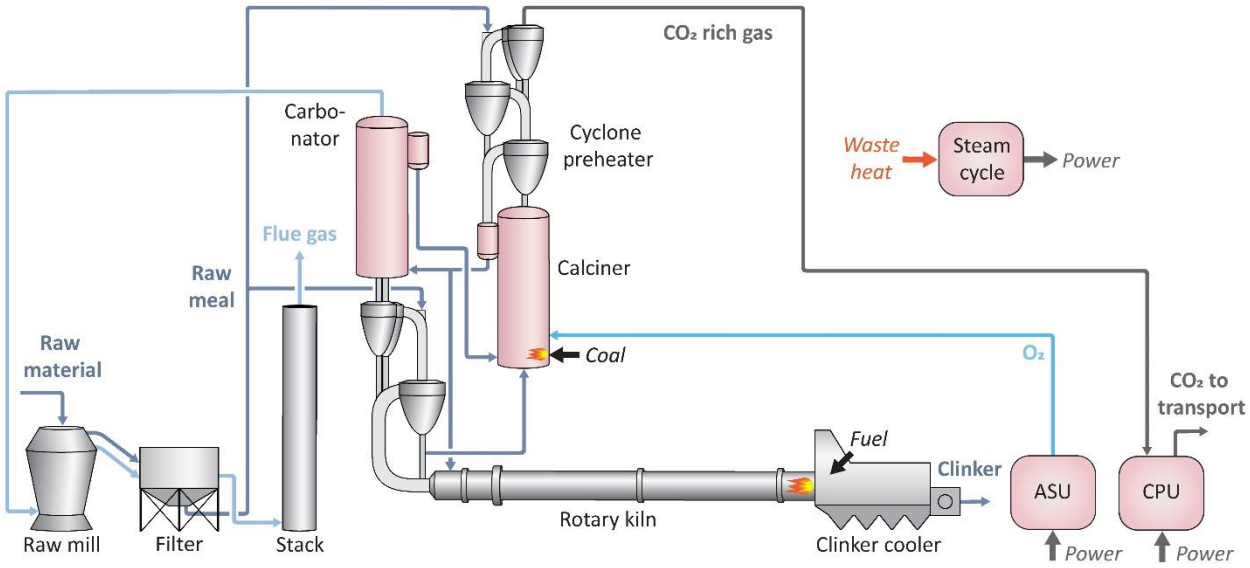

Figure 8. Reference cement kiln with calcium looping CO_2 capture – integrated EF configuration.

2.2 Comparative techno-economic analysis results.

A key element in CEMCAP has been a comparative techno-economic analysis. The basis for this analysis has been the CEMCAP framework (D3.2). Methodologies for the costing of critical components have been established in D4.4, and the overall analysis is presented in D4.6. The difference in maturity of the technologies is accounted for in estimated process contingencies.

The main KPIs from the techno-economic comparison are:

- specific primary energy consumption for CO_2 avoided (SPECCA)
- cost of clinker
- cost of cement
- cost of CO_2 avoided

The calculations were based on process simulations, which in turn rely on input from experimental work carried out in the project (see Appendix A). The results for a defined base case are presented in the following, beginning with a summary of the base-case SPECCA and economic KPIs provided in Table 3.

All the investigated technologies have clearly lower SPECCAs than the reference technology MEA. The oxyfuel technology has a SPECCA of 1.63 MJ_{LHV}/kg_{CO2}, which is the lowest value among the technologies. The chilled ammonia and membrane-assisted liquefaction technologies have SPECCAs of 3.75 and 3.22 MJ_{LHV}/kg_{CO2} respectively, while the calcium looping tail-end and integrated entrained flow technologies have a SPECCA of 4.07 and 3.17 MJ_{LHV}/kg_{CO2}, respectively.

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Table 3. Base case SPECCA and economic KPIs.

	Ref. cement plant	MEA	Oxyfuel	CAP	MAL	CaL - tail-end	CaL – integrated EF
SPECCA [$MJ_{LHV}/kgCO_2$]	N/A	7.08	1.63	3.75	3.22	4.07	3.17
Cost of clinker [€/t_{clk}]	62.57	107.4	93.0	104.9	120.0	105.8	110.3
Cost of cement [€/t_{cement}]	46.01	79.0	68.4	77.1	88.2	77.8	81.1
Cost of CO_2 avoided [€/t_{CO2}]	N/A	80.2	42.4	66.2	83.5	52.4	58.6

The oxyfuel technology shows the lowest cost of clinker compared to the other CO_2 capture technologies, both due to lower variable operating costs and lower capital costs. The absorption-based technologies MEA and CAP as well as both CaL technologies have similar costs, in the range of 105-110 €/t_{clk}. The CaL tail-end technology produces a significant amount of electricity which covers the electricity demand of the CO_2 capture process as well as a part of the cement plant´s demand. As a result, this technology shows a lower electricity cost per ton clinker than the reference cement plant. The MAL technology shows the highest cost of clinker for the base case, with capital costs being the largest individual cost factor. Breakdown of cost of clinker is shown in Figure 9.

The cost of CO_2 avoided is the difference in cost of clinker between the reference cement plant and the cement plant with CO_2 capture, divided by the equivalent specific avoided CO_2 emissions. In terms of CO_2 avoided, oxyfuel has the lowest cost. The CaL technologies also have relatively low costs, especially the tail-end configuration. Break-down of cost of CO_2 avoided is shown in Figure 10.

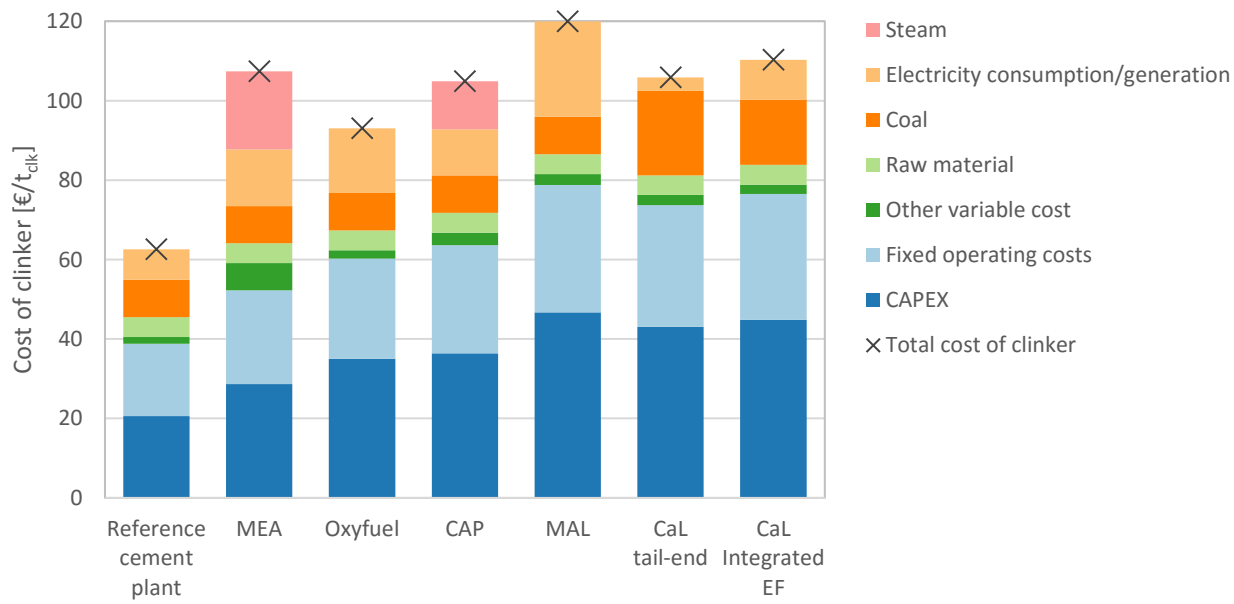

Figure 9. Break-down of cost of clinker for the reference cement plant and the base case of all the investigated CO_2 capture technologies.

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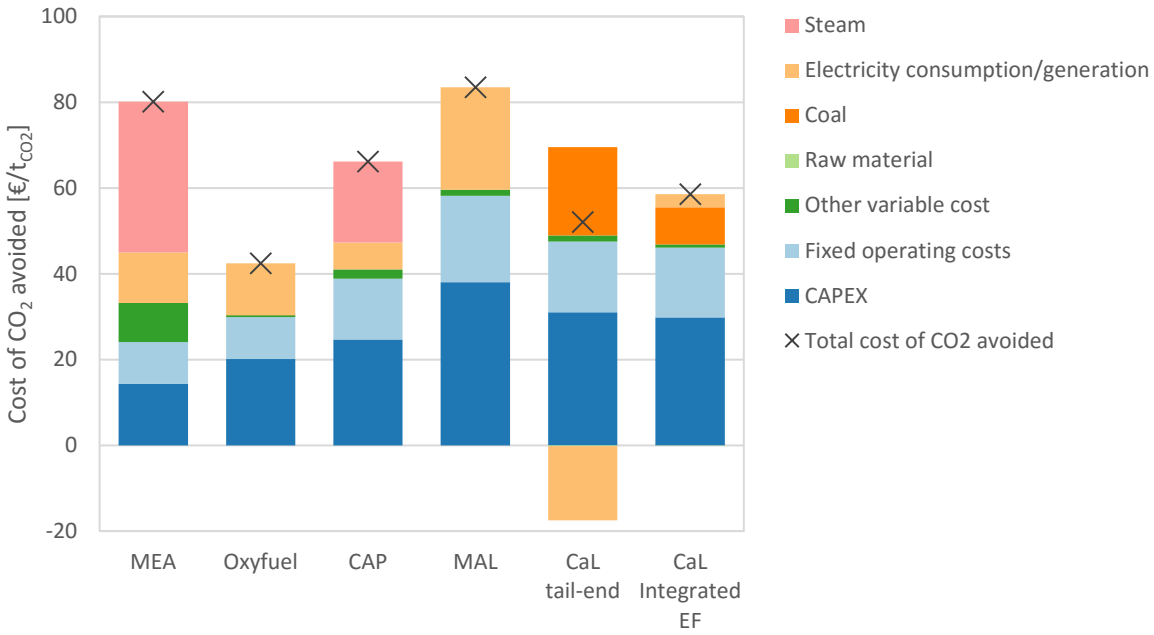

Figure 10. Break-down of cost of CO_2 avoided for the base case of all the investigated CO_2 capture technologies.

Due to the intrinsic uncertainty and the time-place dependency of some assumptions, the sensitivities of the economic KPIs to the following parameters were investigated by performing a parameter variation in the following ranges:

- Coal price: +/- 50% of the reference cost
- Steam supply: +/- 50% of the reference cost
- Electricity price: +/- 50% of the reference cost
- Carbon tax: 0-100 €/t_{CO2}
- CAPEX of CO_2 capture technologies: +35/-15% of the base case estimate

It was shown that the techno-economic KPIs are strongly dependent on these parameters. In particular, MEA and CAP are sensitive to steam cost, CaL technologies are sensitive to coal price, and oxyfuel, MAL, and CaL tail-end are sensitive to electricity price.

The results for carbon tax are shown in Figure 11. Should a carbon tax be implemented, the cost of clinker for the reference cement kiln increases drastically. At a tax level of around 40 €/t_{CO2}, the cost of clinker with oxyfuel technology becomes lower than in the reference cement kiln, and at roughly 60 €/t_{CO2} the CAP and both CaL technologies will have a lower cost of clinker compared with the cement kiln without CO_2 capture. For MEA and MAL, a carbon tax of around 75 €/t_{CO2} would be required for a clinker cost lower than that of the reference cement kiln. The CO_2 emissions from on-site steam generation for CO_2 capture with MEA and CAP have been assumed not to enter the CO_2 capture processes (see CEMCAP framework, D3.2). Due to these direct CO_2 emissions and therefore lower CO_2 avoided, MEA and CAP are more sensitive to a carbon tax than the other CO_2 capture technologies.

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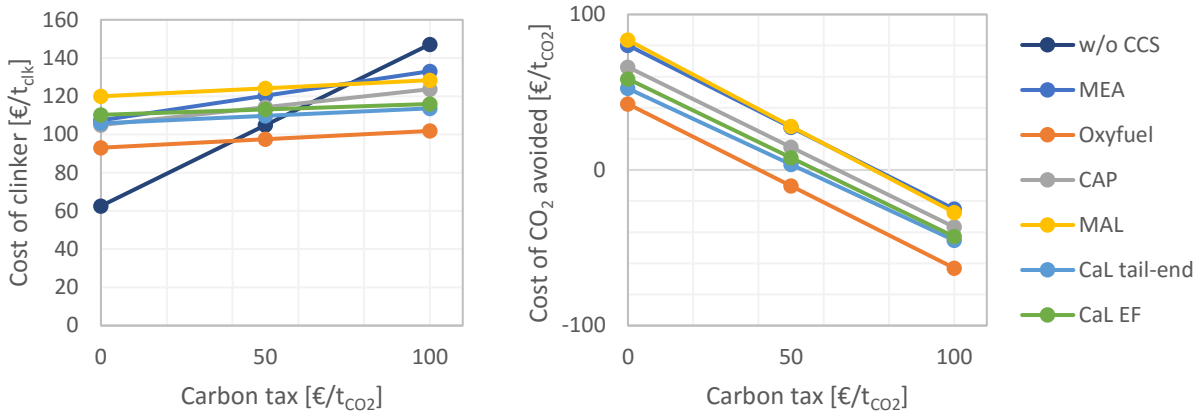

Figure 11. Sensitivity of the cost of clinker and CO_2 avoided to a carbon tax of 0-100 €/t_{CO2}. The effect on the cost of clinker for the reference cement kiln is included for comparison.

The evaluation summarized here and presented in D4.6 was performed for CO_2 capture applied to the Best-Available-Technology (BAT) reference cement kiln defined in the CEMCAP framework (D3.2). It should be noted that cement plants vary in general significantly from each other, for instance when it comes to CO_2 concentration in the flue gas and availability of waste heat.

For the assessment of a CO_2 capture technology for a specific plant, a plant-specific techno-economic evaluation should be performed, due to the dependency on technical and economic parameters that vary over time and between regions. A spreadsheet has been developed in CEMCAP and uploaded to the CEMCAP community in Zenodo to facilitate such evaluations.

2.3 Retrofitability analysis

Cement kilns have a long lifetime (30-50 year or more) and very few, if any, are likely to be built in Europe in the future. The retrofitability of CO_2 capture technologies is therefore an important issue as the implementation of CCS in the cement sector will predominantly be carried out at existing kiln lines. A comparative study was made in CEMCAP of the retrofitability of the different CO_2 capture technologies investigated in CEMCAP, including the reference technology MEA (D4.5). Five different criteria were defined for a qualitative assessment of the retrofitability.

The resulting evaluation of the technologies can be seen in Table 4. The green color means that retrofitability is fairly straightforward, yellow means that some attention is needed, orange means that special attention or further assessment is needed, and red means that retrofit is not possible.

On overall it can be noted that no show-stoppers were identified on retrofitability for any of the technologies. Further, it can be noted that the post-combustion technologies in general are assessed as easier to retrofit than the more integrated technologies.

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Table 4. Comparative assessment of retrofitability of the different capture technologies.

	Criteria	MEA	Oxyfuel	CAP	MAL	CaL (tail-end)	CaL (integrated)
1	Impact on cement production	✓	!!	✓	✓	✓	!
2	Equipment and footprint	!	!!	!	!	!	!!
3	Utilities and services	!	!	!	!	!	!
4	Introduction of new chemicals/subsystems	!	!	!	✓	!	!
5	Available experiences	✓	?	!	?	!	?

2.4 Techno-economic conclusions/recommendations

From the techno-economic evaluation the oxyfuel technology seems most promising, with the lowest CO_2 avoided cost in the base case, followed by the calcium looping technologies. It was however shown that the results are dependent on economic parameters that vary over time and between regions. In the retrofitability analysis it is concluded that the post-combustion technologies in general are easier to retrofit than the more integrated technologies (oxyfuel and integrated EF CaL). Based on these evaluations no clear winner can be pointed out among the technologies. All cement plants are different, both when it comes to conditions relevant for the techno-economic evaluation such as primary energy consumption and CO_2 intensity of the electricity mix, electricity price, steam price, etc., and practical constraints relevant for retrofitability such as space, local electric grid capacity, etc. The technologies investigated in CEMCAP are fundamentally different from each other and provide a portfolio of technologies with different properties. The selection of the optimal technology should be done for each cement plant individually.

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3 CEMCAP INNOVATIONS AND TECHNOLOGY GAPS

CEMCAP research has fostered innovation and filled technology gaps in the field of CO_2 capture for cement and brought technologies to a stage where they are ready for or already progressing towards on-site testing and demonstration. The content of innovation in CEMCAP has largely been the development of new solutions and knowledge to apply new emerging technologies for CO_2 capture in the cement manufacturing process, or the transfer of existing technologies from the power sector, to the cement production process. This chapter summarizes the innovations made in the project as well as the next steps required to continue filling new technology gaps on the route towards full-scale CO_2 capture in cement kilns.

3.1 Oxyfuel capture

3.1.1 CEMCAP innovations

- **The oxyfuel clinker cooler prototype**, using CO_2 for clinker cooling, constructed by IKN and tested at the HeidelbergCement plant in Hannover
- **The clinker extraction device**. This device was invented to enable testing of hot clinker cooling with CO_2 in the oxyfuel clinker cooler prototype. IKN has proven that it is possible to extract a small portion of hot clinker from the kiln. The extraction device will not be of use as such in an oxyfuel kiln process, but it is an entirely new invention, that may be useful for other pilot-scale research on hot clinker.
- **The modification of the oxy-combustion test rig** at IFK, Stuttgart University to enable testing of oxyfuel combustion under conditions relevant for a cement production process (correct temperature and, velocity and location of gas injection to replicate kiln operating conditions).
- **Innovative use was made of an existing commercial kiln burner design** when applied for oxyfuel combustion: A prototype scale oxyfuel burner was manufactured based on a commercial kiln burner design. (POLFLAME burner from Thyssenkrupp). The design is characterized by an arrangement of individual nozzles with adjustable angle for the injection of primary gas with high momentum. It is noteworthy that in CEMCAP it was foreseen that Thyssenkrupp should design a second burner, but this was found not to be necessary for the planned research.
- **The modification of the calciner test rig for oxyfuel calcination** under conditions relevant for a cement production process at IFK, Stuttgart University, including fuel combustion inside the calciner under oxyfuel conditions.

3.1.2 Technology gaps to be closed/the next steps

In sum, the above innovations have advanced the oxyfuel technology so that the next step is demonstration of the full oxyfuel process in cement plants. There are plans for such demonstration in the ECRA CCS project, at Colleferro (IT) and Retznei (AT). Technology gaps to be closed concern:

- Controlling the false air ingress and maintaining it at very low level (oxyfuel process sealings)
- Development of the oxyfuel kiln process control system – will be very different from current systems
- The control of impurities in the captured CO_2. This includes further investigation of the CO_2 processing unit design and operation with exhaust gas from a cement kiln. There is

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however experience from oxyfuel CPU operation for coal power plants (Schwarze Pumpe, DE and Callide, Australia), so this gap has been addressed in other industrial environments.
- Control of the calcination temperature under oxyfuel conditions: since calcination in CO_2-rich atmosphere happens at 50-70 °C higher temperature than what is typical for current kilns.
- A crucial element to be verified in an oxyfuel demonstration kiln is the clinker formation in CO_2/O_2 atmosphere and the resulting clinker properties (whereas it was verified in CEMCAP that cooling of regularly burned clinker in an oxyfuel atmosphere does not affect the clinker properties). Also, earlier experimental work performed in the ECRA CCS project has successfully demonstrated in lab scale, good clinker quality and no detrimental effects can be expected.

An idea that has been discussed among CEMCAP partners, that could merit attention is that both the CO_2 processing unit (CPU) and the cryogenic air separating unit (ASU) could potentially be operated by a specialist company (over-the-fence solution). This would enable cement producers to focus on the oxyfuel kiln operation and clinker burning process.

3.2 Chilled Ammonia Process (CAP)

3.2.1 CEMCAP Innovations

- The direct contact cooler, CO_2 absorber and NH_3 absorber (i.e. water wash) have been tested on pilot scale at GE Power Sweden under operating conditions that are typical for cement plant flue gases. The CO_2 absorption testing has proven that CAP operating conditions can be adapted to reach 90% CO_2 capture with similar CAP design as for CO_2 capture from power plants. It was possible to demonstrate that the ammonia emissions can be limited to below 10 ppm_v. Moreover, the high CO_2 concentrations seen in the cement application foster uptake of ammonia in the NH_3 absorber, enabling a simpler design of this unit, entailing reduced height and complexity.
- Advanced CAP configurations, allowing reduced energy penalty, have been developed by ETHZ, and are currently undergoing IPR protection. These configurations enable reducing the energy consumption of CO_2 capture, but are at a lower TRL than the established and tested CAP process.

3.2.2 Technology gaps to be closed/the next steps

Altogether, the CAP RD&I in CEMCAP have proven that the established CAP process configuration is a technology that is ready for demonstration on site at a cement plant. The main technology gap to fill at this stage is a long demonstration run to prove it in a cement kiln operating environment. A 100,000 t/year CO_2 CAP pilot plant for CO_2 capture from cement has been envisaged by GE. The CAP technology has already been proven at a similar scale for the power sector in several operating environments (gas- and coal-fired power plants (e.g. at Mongstad, NO, and Mountaineer, WV).

The advanced CAP configurations that are newly developed in CEMCAP may be directly applicable at the demonstration scale, as they only rely on common unit operations. However, verification of the promising process simulation results at a smaller pilot scale would of course be useful.

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Similar to what is mentioned above for the oxyfuel CPU and ASU, the over-the-fence solution could be envisaged in CAP applications, either for the necessary steam generation, or for both steam generation and for the CAP plant itself, thus enabling the cement producers to focus on cement production, rather than operating a chemical plant.

If a separate boiler is required for steam generation: Integration of the flue gases produced from the steam generation with the CO_2 capture process.

3.3 Membrane-assisted CO_2 liquefaction (MAL)

3.3.1 Innovative process design in CEMCAP

CO_2 liquefaction has in CEMCAP been demonstrated in a two-step process, enabling that CO_2 can be captured in liquid state at very high purity (99.8% demonstrated with separation from N_2) with relatively low retention time in the separators. This is an important result for future scale-up towards on-site testing of the technology. Also, a stable process control system was developed. Innovations in the process design of the CO_2 liquefaction process have also been demonstrated. The two-stage cascade separation sequence has proven to be viable for combining CO_2 bulk separation (first stage, high pressure) and CO_2 purification (second stage, low-pressure). This design philosophy can be extended in scaled-up configurations to having two or three purification separators at different pressure levels, which will improve the overall efficiency.

3.3.2 Technology gaps to be closed/the next steps

- Long-time performance of different CO_2-selective membranes under realistic operating conditions needs to be verified on site at a cement kiln. Preferably a range of different commercial and pre-commercial membranes should be tested.
- The CO_2 liquefaction has only been tested for N_2/CO_2 separation, and should be tested also with other relevant impurities, to establish the obtainable purity of captured CO_2.

The innovation/technology gap to be filled that lies further ahead, is if/when a suitable membrane can be identified that operates well over long time, and with acceptable power consumption under cement kiln exhaust conditions. The next step would then be the on-site verification of a hybrid process with CO_2 enrichment through a membrane, followed by purification and liquefaction. NOx and SOx removal may be necessary for such a process. For full-scale MAL implementation, the cement kiln should be altered to minimize the false air ingress, in order to increase the CO_2 concentration at the inlet of the process and minimize power consumption.

3.4 Calcium looping (CaL)

3.4.1 CEMCAP innovations

- Tail-end (fludized bed) Calcium looping: innovative use was made of an existing pilot-scale rig at IFK, Stuttgart University. The rig has been successfully operated under unprecedented conditions, replicating cement kiln operation, with high CO_2 concentration at the inlet, and with high make-up ratio, corresponding to the CaO feed to a cement kiln.
- The feasibility of CaL calciner operation with very high O_2 inlet concentrations (up to 53 $vol\%_{wet}$) was demonstrated for tail-end CaL operation. This has been possible due to the thermal energy sink of the endothermic calcination reaction at high make-up rates.

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- A novel Calcium looping CO_2 capture concept for cement plants utilizing entrained flow reactors has been developed and there has been experimental proof of concept. A patent application has been submitted to the European Patent Office for a process to control sulphur, halogens and alkalis in cement plants with Calcium Looping CO_2 capture systems.

3.4.2 Technology gaps to be closed/next steps:

- For both tail-end and entrained-flow calcium looping: a technology gap to be filled is the CO_2 processing unit operation. There is however experience fromr oxyfuel CPU operation for coal power plants (Schwarze Pumpe, DE and Callide, Australia), so this gap should be minor.
- Tail-end Calcium Looping: On-site demonstration at a cement kiln would be the next step.
- Entrained flow Calcium looping: A Calcium Looping entrained flow CO_2 capture demonstration plant will be constructed within the H2020 project CLEANKER, that started in October 2017. Technology gaps to be closed for Integrated Calcium looping in CLEANKER:
    - The technology needs to be tested in the integrated form (calciner and carbonator working together) in realistic conditions reproducing the industrial situation.
    - The impact of raw meal quality needs to be investigated in order to understand its impact on the sorbents CO_2 capture properties/performance.
    - The process control system must be developed.

3.5 The kiln operability technology gap

The operability of cement kilns with CO_2 capture is a technology gap that cannot be closed without on-site demonstration of the CO_2 capture technologies. This is a vital element for successful full-scale implementation of CO_2 capture in the cement industry. It is currently assessed that the operability of the integrated technologies, i.e. oxyfuel and integrated CaL, could be more challenging than for the other technologies, which are end-of-pipe. For amines, CAP and tail-end CAL there are experiences with operating the capture technology at coal-fired power plants: Amine technology has been installed at the Boundary Dam coal fired power plant in Saskatchewan, Canada (capacity 1 Mt CO_2 per year), CAP has been demonstrated on a slip stream from the Mountaineer power plant in West Virginia (corresponding to thermal input of 50 MW) and tail-end CaL has been demonstrated on site at the La Pereda coal-fired power plant in Spain (heat input 1.7 MW fuel)

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4 CO_2 USE IN THE CEMENT INDUSTRY

4.1 Introduction

Due to the use of carbonates as raw materials, the cement industry will have continuous inherent process emissions of CO_2 also in a low carbon future, whereas other emission sources such as fossil power plants may be almost eliminated by 2050. This may offer an opportunity, as CO_2 can substitute fossil- or biomass-based carbon sources, in manufacturing a wide variety of products, including fuels, polymers and bulk and specialty chemicals. On the other hand, CO_2 is a very stable molecule, and its conversion processes are normally highly energy intensive. The form (heat, electrons, photons) and quantity (correlated to the process efficiency) of energy demanded are determinant of whether a CO_2 Capture and Utilization (CCU) process will have: i) a positive impact on climate change mitigation and ii) a business case.

4.2 CEMCAP research on post-capture CO_2 management

Within CEMCAP, we have inventoried 16 possible CO_2-based products, and evaluated their markets, the potential for CO_2 utilization and abatement, listing merits and challenges for each product in question (D5.1). We have concluded that CO_2 utilization routes currently available and under development offer limited opportunity for climate change mitigation in the cement industry context. The reasons for that are either process limitations (e.g., the energy demand is too high), or product limitations (e.g., the existing market is limited).

For illustration, we can consider the reference CEMCAP cement plant, which emits 0,85 Mton CO_2 per year. To convert that amount of CO_2 into ethanol, even in a very idealized situation in which all process inefficiencies are eliminated, more than 900 MW_e are required. It is unrealistic to assume such power would be available as excess production from a grid. The Walney Extension, the world's largest wind farm, has a nominal capacity of 659 MW_e – and covers an area in the Irish sea larger than 145 km^2. Other products, such as cyclic carbonates, do not have such a high energy demand. However, cyclic carbonates are fine chemicals with typical plant capacities around 10 ktonne per year, while the largest plant has a capacity of 60 ktonnes per year. Assuming an average CO_2 content of 40 wt%, a typical plant would lead to the utilization of 4 ktonnes/year of CO_2 or 0.5% of the emission from a BAT cement plant.

The results of the products evaluation is given in Table 5 and Table 6 in semi-quantitative terms. The analysis shows that no evaluated product has good scores for all the evaluated metrics.

Table 5: Definition of metric levels for Table 6.

Metric	Icon	Bad	Intermediate	Good
Product Market		Below 10 Mt/year	10-100 Mt/year	Above 100 Mt/year
Energy demand		Carbon oxidation state above 2	Carbon oxidation state between 0 and 2	Carbon oxidation state below 0
Technology Maturity		TRL < 5	5 ≤ TRL ≤ 7	TRL >7
Product price		Below 200 €/ton	200-500 €/ton	Above 500 €/ton

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Table 6: Visual summary of the results for CCU products.

Product	Market	Energy demand	Maturity	Price
$CaCO_3$ (GCC)				
$CaCO_3$ (PCC)				
Aggregates				
Carbonated concrete				
Methanol				
DME				
Methane				
Ethanol				
Isopropanol				
Biodiesel from microalgae				
PPC				
Polyols				
Cyclic carbonates				
Formic acid				
CO_2 (food-grade)				
CO_2 (greenhouses, NL)				

Different CCUS chain evaluations were made, as summarized in Table 7. In CCS1, the CO_2 is assumed to be captured from a cement plant in Belgium and stored in the Dutch continental shelf. In CCS2, the CO_2 is captured from a cement plant in Germany and stored in the Norwegian continental shelf. The results of the two proposed saline aquifer cases make it clear that the estimated results are dependent on the CCS chain configuration: as the CO_2 transport mode changes, both the cost and the amount of CO_2 avoided are affected. The mineralization (CCS3) base case with current technology efficiency, leads to a CO_2 capture rate of 62%, and thus the CO_2 avoidance is relatively low. When a possible process improvement is considered, and the capture rate is increased to 90%, CCS3 becomes cost competitive with CCS2.

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The optimal CCS solution for each cement plant will be location-dependent. In terms of maturity and scale, CO_2 storage is to be considered commercially mature on the required scale and above, whereas the mineralization option requires considerable development, piloting and demonstration, as well as scale-up.

When combining CO_2 utilization and geological storage (CCUS), three different scenarios were evaluated – U1: making a fuel (ethanol); U2: a polymer feedstock (polyols), and U3: food-grade CO_2. For the ethanol case, the high electricity demand for the hydrogenation route limits the CO_2 utilization to ca 24 kton, or 3,1% of the emissions of the reference CEMCAP cement plant. When ethanol from sugarcane is available, the CCS1+U1 scenario leads to about the same cost per ton of CO_2 captured as that for CCS1. Therefore, the climate mitigation potential of integrating ethanol production to the CCS chain is low, and the impact on the economic results are negligible. On the other hand, when the synthetic ethanol is used to displace ethanol from wheat, both the CO_2 avoidance and the business case are significantly improved. This scenario illustrates that *the potential sustainability of a CCUS chain (as opposed to the CCS alternative) is greatly dependent on the CO_2 footprint of the product being displaced*.

For the polyol case (CCS1+U2), the high value of the end product in combination of the displacement of a CO_2-intensive raw material (ethylene oxide) lead to a positive business case. For the food-grade CO_2 case (CCS1+U3), there is no climate mitigation potential. The impact on the business case is relatively small, and dependent on the origin of the CO_2 being displaced.

Table 8. Results of the CCUS chain evaluations.

Scenario	CO_2 sequestrated (kton/year)	CO_2 utilized (kton/year)	CO_2 avoided (kton/year)	Cost €/ton CO_2 avoided
CCS1	694	0	504 (*basis*)	114 (*basis*)
CCS2	694	0	469 (-7%)	153 (+34%)
CCS3				
Base case, current technology	478	0	238 (-53%)	394 (+173%)
Improved process	694	0	449 (-11%)	156 (+37%)
CCS1+U1				
Displacing ethanol from sugarcane	670	24	518 (+3%)	111 (-3%)
Displacing ethanol from wheat	670	24	600 (+19%)	96 (-16%)
CCS1 + U2	637	58	708 (+40%)	-18 (-115%)
CCS1 + U3				
Displacing fossil $_{CO2}$	644	50	504 (same)	108 (-5%)
Displacing CO_2 from fermentation	644	50	504 (same)	120 (+5%)

As a general conclusion, it is clear that for full scale cement plants, CO_2 utilization should be considered in combination with storage, as the amount of CO_2 likely to be utilized is lower than 10% of the total emissions. The production of high added-values products and the displacement of CO_2-intensive raw materials may improve or even lead to positive business cases for the integrated CCUS chain. However, the possibility of having a positive business case (with no taxation of CO_2 emissions in place), may be restricted to few niche applications, as only polymers and cyclic carbonates were identified as having high prices and low energy demands (Table 6).

Further insight on the difference between CCS and CCU is provided in Appendix B.

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5 PATHWAYS FOR FUTURE LOW-EMISSION CEMENT PLANTS

5.1 CCS implementation in the cement industry for climate protection

5.1.1 The climate protection context in brief

The IPCC special report released in October 2018 is stressing the need for significant cuts in CO_2 emissions from industry (75-90%) to reach the 1.5 °C target. It can also be seen in the report that is not unlikely that implementing CO_2-negative technologies may be required. Cement production today contributes with 6-7% of man-made CO_2 emissions to the atmosphere [5]. The demand of cement as a key commodity for construction and societal development as well as the high share of related process CO_2 emissions are the cause that this industrial segment will continue to produce CO_2 also in a low-carbon future. In the IEA/CSI cement technology roadmap 2018 [6], more than 50% of the emissions reduction from cement production is attributed to CCS. Altogether, CO_2 capture from cement is defined as the required key breakthrough technology by CEMBUEARU and the necessary first part of a CCS/CCU chain in a future low-carbon or CO_2 neutral world [7].

5.1.2 CO_2 capture from cement production is possible and CEMCAP has expanded the technology options

CO_2 capture is already possible on industrial scale with amine capture, which is the chosen technology for the Norcem cement plant FEED study on full-scale CO_2 capture. CEMCAP has shown that CO_2 capture from cement kilns is possible with five additional technology options, meaning that there is a family of technically possible capture technology options for future CO_2 emissions abatement in the cement industry. The technologies tested in CEMCAP are now ready for or already progressing towards on-site testing and demonstration in cement plants. It is therewith at the conclusion of the project possible to envisage how the five investigated CEMCAP technologies can move further along their different technology pathways towards full-scale implementation.

Provided that these opportunities are pursued, it is clear that low-CO_2 emission or even CO_2-neutral cement production will be technically possible to deploy in the future. Realising such cement production will however require firstly that the envisaged testing and demonstration of CO_2 capture continues and does not come to a halt after CEMCAP, as illustrated in Figure 12. Secondly, it is key to provide a clear perspective towards the future application of CO_2 capture technologies in the cement industry. This will require funding for the necessary technology demonstration and the development of a long-term economic framework for capture technologies (see also Section 5.3).

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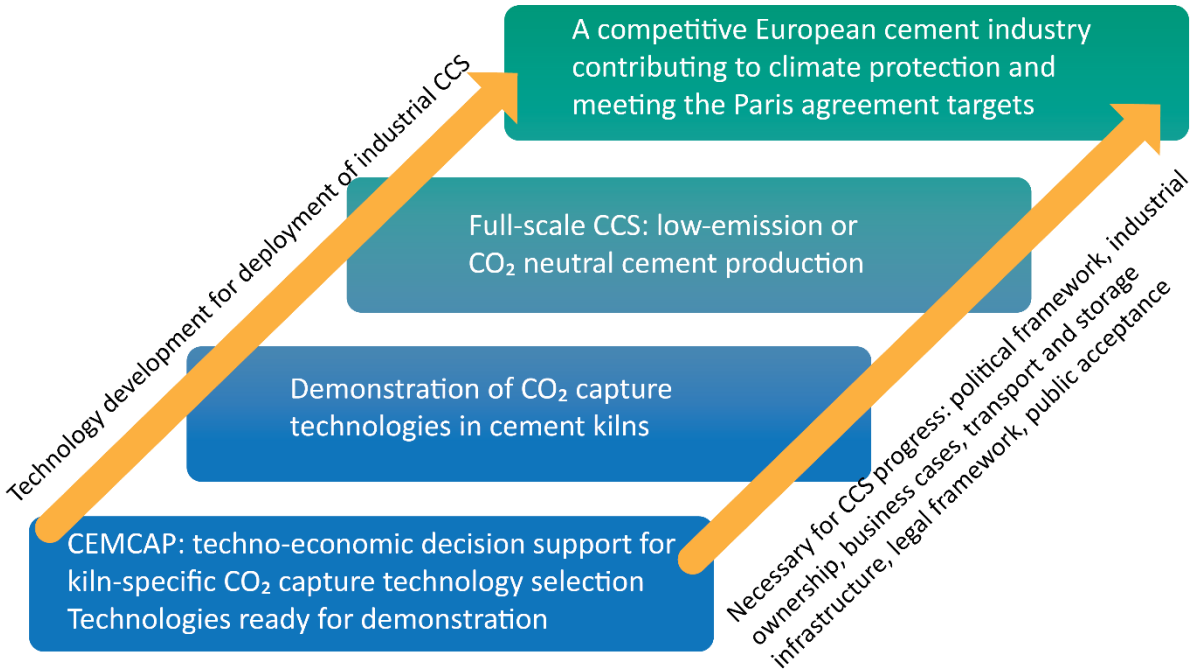

Figure 12. The pathway from CEMCAP towards competitive cement production contributing to climate protection.

Importantly, on the technology development side, there will be a need for technology suppliers that can deliver the CO_2 capture technology to the cement industry that is required for CCS deployment. A massive deployment of CCS in a few decades will be required to meet climate targets, and there must be technology suppliers that are capable of meeting the demand. The CEMCAP consortium has comprised GE, thyssenkrupp and IKN, which has been important both for the project execution, and for contributing to knowledge-building among technology suppliers.

5.1.3 BECCS and cement production - a cost-efficient carbon-negative option?

The IPCC special report released earlier this year highlights BECCS (BioEnergy with CCS) as an important carbon-negative measure. (Co-)firing of biomass in cement kilns with CO_2 capture can be a cost-effective BECCS option and an additional element of the future technology pathways for CCS in the cement industry. The reason is that approximately one third of the CO_2 emissions from cement kilns comes from fuel combustion and two thirds from the calcination of $CaCO_3$ into CaO. Therewith there is an economy of scale for installing and operating CO_2 capture technology in a cement kiln, since, when burning the same amount of biofuel, BECCS as an integrated part of CCS in the cement kiln could have a potential to be more cost efficient per tonne of CO_2 captured than BECCS in a power plant, where all the CO_2 comes from the fuel. Especially, the use of alternative fuels from waste materials with biogenic content in cement plants avoids any landfilling and allows to use fully sustainable sources of biomass, that are not related to any additional land-use or land management. The capture of the biogenic carbon content of waste materials through fuel use in cement plants equipped with CCS technology therefore minimises indirect CO_2 emissions, which are often related to other forms of BECCS, when they are based on additional production of biomass [14].

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Furthermore, the application of cement from CCS cement plants has to take into account the CO_2 absorbed by concrete during its lifetime. The process of partial recarbonation of concrete absorbs CO_2 from the atmosphere throughout the lifecycle of constructions and at its end [7] when the concrete structures are demolished, and fresh surface is exposed to the atmosphere. Consequently, the permanent storage of CO_2 in mineral building products gives permanent CO_2 removal from the atmosphere. More information about carbonation of calcium silicates as a technology for permanent removal from the atmosphere can be found in one of the ECRA/CSI technology papers from 2017 [15].

5.2 The kiln operator's perspective on future low-carbon kilns

5.2.1 The need for kiln-specific CO_2 capture cost analyses

The participation in CEMCAP of the dedicated partners HeidelbergCement, Italcementi and Norcem is one of several clear proofs of the will within the cement industry to take ownership and move forward towards implementation of CO_2 capture. Cement kilns have a long lifetime (30-50 year or more) and very few, if any, are likely to be built in Europe in the future. The cost of retrofitting CO_2 capture to existing kilns is of course an essential element when evaluating which kilns are relevant for installing CO_2 capture technology, and what technology to choose. In order to evaluate CO_2 capture retrofit for any specific cement kiln, each cement producer will have to make its own assumptions and analyses. Cost assessments and assumptions in CEMCAP have aimed at full transparency. The framework document and the techno-economic results can contribute to the knowledge base for in-house assumptions and enable analyses to be as accurate as possible.

5.2.2 Kiln operator's perspective on installing CO_2 capture

The core business of a kiln owner, when implementing CO_2 capture, is to produce cement with maintained high product quality. From this perspective, the preferred scenario would be easy retrofit of CO_2 capture at a low cost, and that the energy penalty and additional cost for operating the kiln is low. Also, the kiln operation should preferably not be much more complicated than before, and the down-time for installing CO_2 capture equipment should be as short as possible. CEMCAP has shown that there will be a trade-off between these requirements: capture technologies with relatively low energy penalty have higher integration and are therefore likely to be more challenging to retrofit. Furthermore, as mentioned earlier, process units that are not familiar to the kiln operators can be envisaged as over-the-fence solutions, i.e. operated by a contractor. Additionally, taking the kiln-owner's perspective, disposal of the captured CO_2 should be easy and come at a reasonable and affordable cost.

5.2.3 Securing a stable fuel supply for kilns in the future

Coal is the main fuel employed for cement production. This may not be obvious in a fossil-fuel constrained low-carbon future. Therewith, in order to be able to operate also in 2050, kilns will need fuels that can be burnt at sufficiently high temperatures. Biomass and solid residual fuels (SRF) are options for the future cement production, and as stated above, kilns with CO_2 capture can, from this perspective, indeed have an advantage in that they can enable carbon-negative cement production. However, it is not unlikely that there will be some competition for biomass available for combustion in the future, and it is uncertain how many kilns will actually be able to operate on biomass.

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5.3 Required: stable long-term policy, business cases and more

CEMCAP has enabled drawing up the rough pathways for the low-emission cement kilns of the future – using the results from the techno-economic analysis and describing what the next steps are to continue to close technology gaps and climb the "technology readiness ladder" towards commercially available CCS in the cement industry. In order to implement cement production with CO_2 capture, for further CO_2 transport and storage, and therewith contribute to climate protection, technology development is not sufficient for implementation in cement kilns, as illustrated in Figure 12. As a technology-oriented project, CEMCAP has not addressed how to resolve non-technical obstacles to CO_2 capture realisation, but it is clear that these cannot be neglected.

Above all, **a political framework and commitment** is needed for CCS implementation. If the European energy-intensive industries are to achieve the political targets that the European countries have committed to after the Paris Agreement, CCS is mandatory. Significant CO_2 emissions cuts from cement production or other energy-intensive industrial sectors cannot be achieved with current regulations and accompanying financial framework, including the current Emissions Trading System (ETS).

Measures that provide **financial incentives and long-term predictability**, are required to create business cases for CO_2 emissions abatement at competitive costs. With the current situation, even with 100% coverage for investment costs, the OPEX incurred by CO_2 capture is too high to bear by the industry alone. It is therefore necessary to establish a link between the production and consumption along the value chain and the lifecycle of use of the product. Measures to reflect the CO_2 cost, like the emission trading schemes (ETS), need to become more predictable. Especially they need to be aligned with effective measures and policies that prevent the shifting of production out of a system with cost for CO_2. Otherwise, CCS implementation in Europe will not be feasible due to the risk of *carbon leakage*, i.e. that production processes with CCS for e.g. low-carbon cement or steel will result in industrial products that are too expensive on the market and would therefore be replaced with products manufactured without CCS.

Furthermore, there are **legal and regulatory aspects of CCS** that must be addressed and met for e.g. trans-boundary transport of CO_2 as well as CO_2 storage. Also, public perceptions and the necessary **public acceptance of CCS** as a measure to combat the ongoing global warming and reverse climate change is an important aspect, that was only briefly touched upon in CEMCAP in D2.10. Furthermore, an **acceptable, efficient and reliable CO_2 transport infrastructure**, as well as **sufficient and reliable CO_2 storage** are required for CCS implementation and acceptance.

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A SUMMARY OF CEMCAP EXPERIMENTAL RESEARCH

A.1 Oxyfuel experimental research: burner, calciner and clinker cooler

A 500 kW combustion tests facility at University of Stuttgart was successfully adapted for burner demonstration tests under conditions relevant for cement kilns. A prototype oxyfuel burner was manufactured taken as a base a commercial kiln burner design (POLFLAME burner from thyssenkrupp).

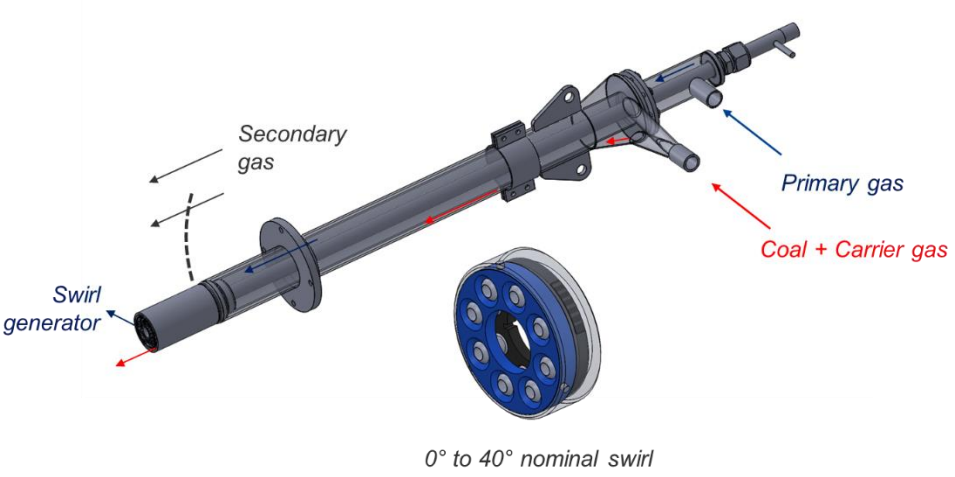

Figure 13. Burner prototype design for oxyfuel combustion.

Oxyfuel demonstration tests were carried out with the downscaled burner (D7.2). Combustion performance under oxyfuel conditions was compared to conventional combustion with air in terms of gas temperature, radiation profile, heat fluxes to wall, burnout and concentration of main species along the furnace (CO, CO_2, O_2, NO_x, SO_2). Four different fuels were used: a German lignite coal, petcoke, lignite and SRF. Key operational parameters were identified to optimize burner operation under oxyfuel conditions.

CFD simulations of selected oxyfuel cases were validated against the experimental results, after which a full-scale cement kiln with an up-scaled burner in oxyfuel mode was simulated (D7.3).

Key conclusions from the oxyfuel burner experimental work

- A burner design with single nozzle arrangement was proven to be suitable for oxyfuel operation.
- Oxygen enrichment in primary gas is an additional variable that can be used to optimize fuel ignition and CO formation in the near burner area
- Total oxygen content in combustion gas and swirl angle should be adjusted to produce similar temperature profile and heat transfer to walls as in air firing conditions.

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Oxyfuel calciner

An existing, electrically heated calciner test rig at University of Stuttgart was modified to enable oxyfuel calcination under conditions relevant for a cement kiln. The modifications included the gas mixing station, temperature measurements, pre-heating arrangements of fuel and raw material, the raw meal injection system and fuel addition inside the calciner (D8.2, D8.3).

Key conclusions from the oxyfuel calcination experimental work

- Calcination can be carried out in oxyfuel atmosphere with an increased temperature level, 920°C-940°C, compared to air calcination temperature at 860-880°C.
- Calcination is a fast reaction once the raw meal particle reaches the required equilibrium temperature, the calcination is completed within seconds, provided that the energy (heat) is available to proceed the reaction.
- Raw meal particles did not show tendency to increase the deposit build up at elevated (oxyfuel) calcination temperature, but this phenomenon needs further study regarding long term deposit build-up in industrial scale calciner regarding the impact of ash species, especially the alkalis (K/Na), S and Cl cycle in the preheater-calciner-kiln system

Oxyfuel clinker cooler experimental work

A single-stage cooler prototype was designed taking into account the potential for up-scaling as well as technical feasibility to be operated in prototype scale. The oxyfuel clinker cooler prototype was constructed by IKN and assembled in the HeidelbergCement plant in Hanover.

During the trials several unexpected experimental challenges (e.g. unstable clinker extraction and feed to the pilot clinker cooler, damage of the hot clinker extraction tube and false air ingress) were encountered. The challenges related to the clinker extraction do not apply to full scale oxyfuel technology application but are limted to the operation of a pilot clinker cooler in the CEMCAP project. All challenges were resolved by VDZ, IKN and HeidelbergCement during an extended experiment campaign. The clinker cooler pilot plant was successfully operated, measuring campaigns were performed and clinker samples with high product quality were taken and further analyzed in VDZ. Clinker production rate up to 47 t/d was demonstrated. Despite the significant false air ingress in the pilot cooler, CO_2 concentrations exceeding 70 Vol.% were reached during the experiments (D9.2).

Key conclusions from the oxyfuel clinker cooler experimental research

- Clinker analysis revealed no negative effects on cement strength. Therefore, the experiment confirmed that it is possible to cool down clinker in oxyfuel conditions in industrial environment, as no relevant impacts neither on clinker quality nor on cement strength have been observed.
- High CO_2 purity can be achieved by subsequent CO_2 purification (CPU) with low energy demand in the CPU (D6.1). It is based on very high initial concentration of CO_2 in the oxyfuel process, including the clinker cooler.
- False air ingress is expected to have a much lower impact on the operation of industrial scale oxyfuel clinker coolers due to scale effects.
- The operation of the oxyfuel clinker cooler prototype revealed that boundary zones such as the cold clinker discharge system demand special attention regarding minimization of false air ingress also in industrial scale projects.

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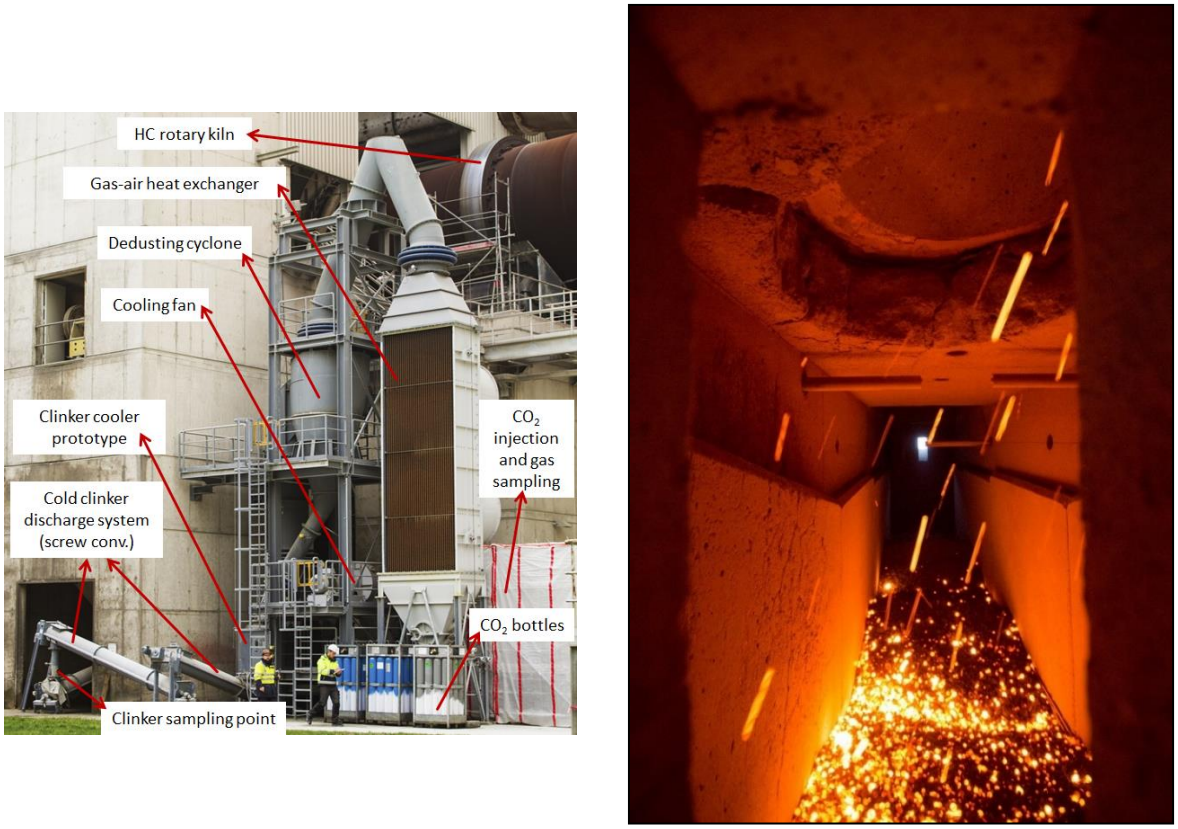

Figure 14. Oxyfuel clinker cooler pilot plant overview (left) and commissioning (right).

A.2 CAP experimental research: direct contact cooler, absorber, water wash

Pilot plant tests were performed in the 1t/day pilot plant at the GE laboratories in Växjö, Sweden. Due to significant simulation-based preparation work and joint efforts in optimizing the procedures, the CEMCAP researchers were able to conduct 144 tests in total, significantly more than originally foreseen. All process units that are directly affected by a change of flue gas (e.g. by the increase of CO_2 concentration when moving from power to cement applications) have been demonstrated and have shown very encouraging results.

<u>CO_2 absorber</u>

The CO_2 absorber tests represent the core of the test work done within CEMCAP. The CO_2 absorber test were used in regressing the parameters of the newly developed rate-based model.
The testing of the CO_2 absorber was split in several test campaigns, based on the principle that the tall commercial absorber can be split in several 3 m packing sections (3 m is the height of the packing in the pilot plant). Such splitting was enabled by detailed simulations of the tests prior to testing.

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All sections of the CO_2 absorber were successfully tested with a broad range of operating conditions, varying

- Temperature
- NH_3 and CO_2 concentration (of both liquid and vapor stream)
- L/G flowrate ratio
- Superficial velocity of the vapor phase

Direct contact cooler (DCC)
In the reference cement plant, the absence of a desulfurization unit (DSU) requires the reduction of SOx before the flue gas enters the CO_2 absorber. Despite the fact that the NH_3-solvent is chemically stable in the presence of SOx (contrary to amine-based absorption processes), the reduction of the CO_2 uptake potential through absorption of SOx provides enough motivation to reduce the SOx impurity level. The pilot campaign tested the integration of desulfurization in the DCC.

NH_3 absorber
The NH_3 absorber was successfully tested with a broad range of operating conditions, varying the same parameters listed above for the CO_2 absorber. Successful reduction of NH_3 concentrations to the targeted 200 ppm within only 3 m of packing could be proven. The remaining reduction to below 10 ppm will then be achieved using an acid wash stage. The acquired experimental data was used to validate the newly developed rate-based model.

In addition, lab-scale experimental work at ETHZ has continuously supported the pilot test planning, execution, and interpretation by improving the intuitive understanding of the complex system thermodynamics and by providing tools and experimental procedures.

A.3 MAL experimental research: membranes and CO_2 liquefaction

Membrane material testing
Two polymeric membrane materials, a commercial perfluoropolymer-based membrane and a pre-commercial PEBAX-based membrane, were tested in bench scale at TNO in Eindhoven. The main results of interest from these experiments were the permeabilities and selectivities of the membrane material, that is, the ability of the material to favour CO2 over the other components present in the gas mixture. Both membranes tested showed intrinsically very high separation factors, and neither showed any plastization effects at high CO_2 concentration and high relative humidity. For the commercial membrane material, 78 mol% CO2 concentration was measured on the permeate side, which is a very favourable feed concentration for subsequent CO2 separation by liquefaction. Selectivities observed were roughly 20 and 45 for CO2/N2 for the two respective membranes.

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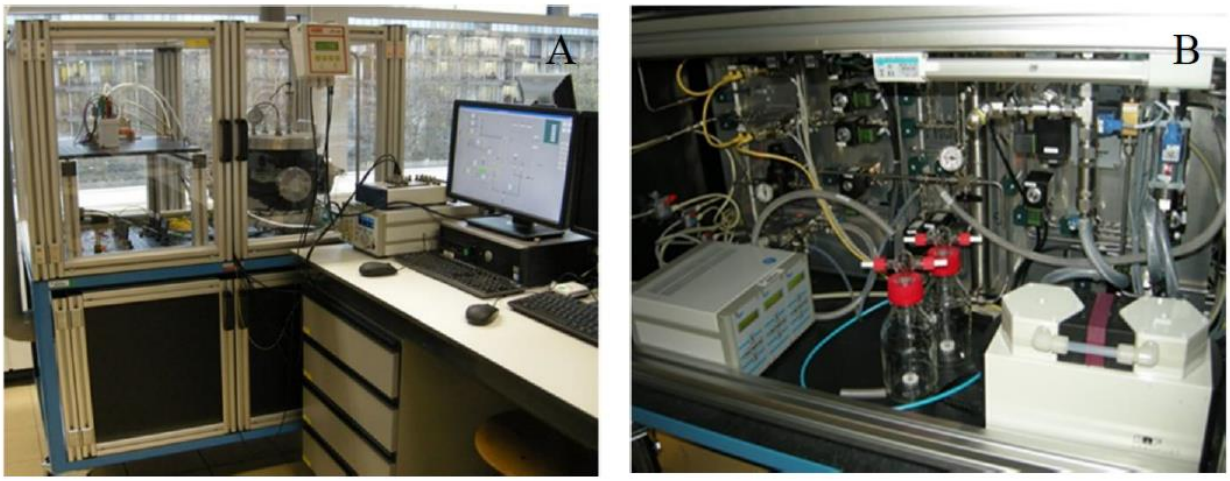

Figure 15. (A) Experimental set-up for the controlled mixing of gases, application of gas mixes to the system of study, and computer control. (B) Hardware for creating feed gas conditions using a multitude of mass flow controllers (top left), and an evaporator (bottom left) or wash bottles (bottom centre) to control relative humidity of the feed gas.

Key conclusion from membrane material testing

- It was demonstrated that from the separation characteristics and data reported on pilot studies, one of the tested membranes can comply with the concentration requirements in membrane assisted CO_2 liquification.

CO_2 separation and purification by liquefaction

Testing of CO_2 separation and purification by liquefaction was performed in a laboratory pilot plant at SINTEF Energy Research in Trondheim (D11.2). The maximum capacity of the facility is in the range 10–15 t/d, depending on the gas composition used. The performed experiments represented a somewhat simplified gas composition compared to the actual expected composition. Binary mixtures of nitrogen and CO_2 were used to emulate permeate gas achieved by front-end flue gas separation by polymeric membranes and subsequent dehydration. The pilot facility was built and commissioned in parallel with the CEMCAP project, and the main test campaigns were performed during the fall of 2018. Around 6 t/d flowrate was used in the experiments.

The main results of interest were those related to the quality of separation, that is, the purity of the final CO_2 product as well as the CO_2 capture ratio. Dimensions and achieved liquid retention time in the gas-liquid separators are of a scale relevant to understanding the operational and process control challenges in industrial-scale and full-scale plants.

Very promising results were achieved in the experiments. Most results corresponded well to expectations based on steady-state simulations. CO_2 purities up to 99.85 mol% were measured and the CO_2 capture ratio corresponded well with expectations. Although the presence of other volatile components such as O_2 and Ar would influence the purity of the CO_2 liquid product, the experiments gave strong indications that purities very close to those predicted from controlled vapour-liquid equilibrium measurements is obtainable.

Robust operation was experienced and stable conditions in the separators could be achieved with the control system. Temperatures were normally between -53°C and -56°C in the separators. Since

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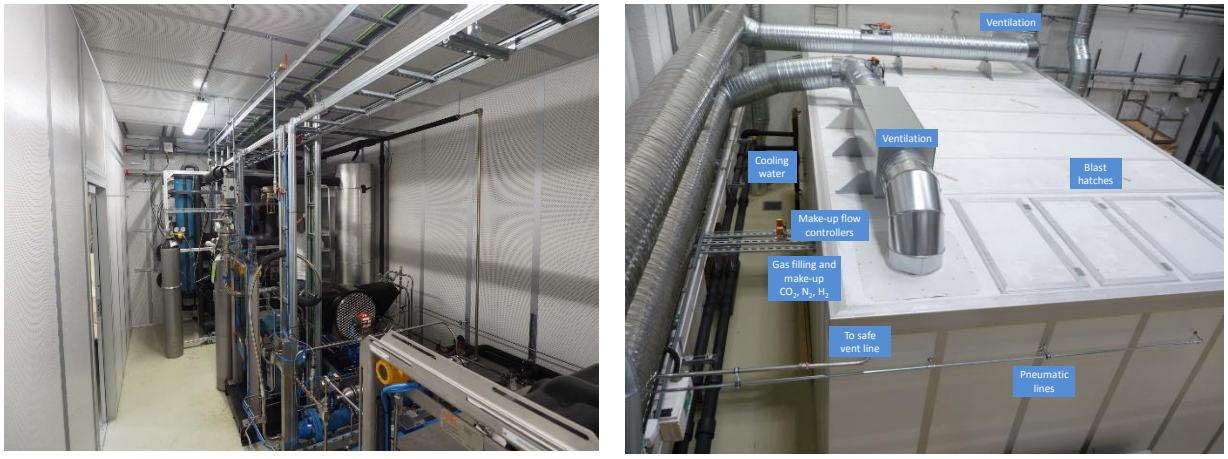
the closed-loop process, which has considerable feedback loops affecting the operation, could be controlled and stabilized by the control system, it is reasonable to conclude that an actual, open process can be controlled by the same control structure as that used in the experimental runs.



(a) (b)

Figure 16. Interior (a) and exterior (b) of the low-temperature CO_2 liquefaction unit.

Key conclusion from CO_2 separation and purification by liquefaction

- CO_2 in membrane permeate gas can be efficiently separated and purified by low-temperature CO_2 liquefaction. The process operation is stable, robust and easily scalable to larger capacity.

A.4 CaL experimental research: circulating fluidized bed and entrained flow

Circulating fluidized bed (tail-end) calcium looping

The Calcium Looping process using the circulating fluidized bed technology was demonstrated at semi-industrial scale at USTUTT's 200 kW_{th} Calcium Looping pilot facility yielding very high CO_2 capture efficiencies (up to 98 %). In total five experimental campaigns were conducted at USTUTT's pilot facility, comprehensively covering the field of operational conditions relevant to the Calcium Looping technology's application in the clinker production process, investigating parameters such as high make-up ratios, CO_2 concentrations up to 33 $vol\%_{wet}$, carbonator temperatures between 600 to 710 °C, and looping ratios up to 20 mol_{CaO}/mol_{CO2}, two different reactor configurations and two limestone qualities (D12.3).

The screening of operation conditions at CSIC's 30 kW_{th} plant showed that CaL design parameters for cement plant applications are in agreement with those for power plant application (D12.1).

Key conclusion circulating fluidized bed (tail-end) calcium looping

- Calcium Looping CO_2 capture using fluidized bed systems has been demonstrated in industrially relevant conditions by extensive experimental investigations and can be considered to be ready to be applied in the cement industry for CO_2 capture in in larger scale industrial demonstration activities.

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Entrained-flow calcium looping

A novel concept of using entrained flow reactors for Calcium Looping CO_2 capture has been developed and its general concept was proven by experimental investigations at CSIC and USTUTT. At entrained flow conditions, the carbonation reaction follows a pseudo-homogeneous kinetic model, first order in respect to CO_2, with a small positive effect of water vapour in the gas and a linear dependency of the sorbent's CO_2 carrying capacity. It was shown that entrained flow calcined raw meal hold considerable CO_2 carrying capacities enabling an entrained flow CaL CO_2 system based on cement raw meal (12.2).

Key conclusion entrained-flow calcium looping

- The less mature entrained flow Calcium Looping concept proved to be a promising technology. However, further research is required beyond CEMCAP to increase the maturity level of this technology before its commercial application for CO_2 capture from clinker manufacturing. (To be done in the ongoing H2020 CLEANKER project).

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B ON THE DIFFERENCE BETWEEN CCS AND CCU

It is important to recognize fundamental differences in their mitigation potential for CCS and CCU. Figure 17 represents a full CCU system (CO_2 from a cement plant converted in a fuel for transport) and its reference system without CCU, following common rules to define such reference (i.e. including the same ingredients in both systems [11]). It is particularly important to focus only on the fossil carbon residing in the carbonates contained in all raw meal used to make clinker and then cement.

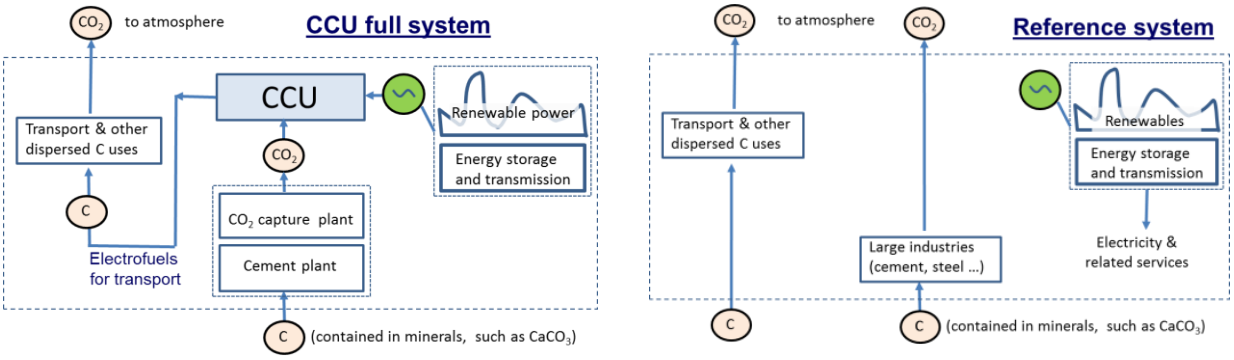

Figure 17. Schematics of a CCU system and its full reference without CCU, referred to process carbon emissions only.

Due to the short life of the fuel carbon product, it is evident that the CCU system illustrated on the left-hand site of Figure 17 can only mitigate 50% of the emissions of the original reference system. This maximum mitigation goes down when accounting for the additional energy requirements of the CO_2 capture step and the possible carbon footprint of renewable energy. Most important: since the reference system without CCU has "available" a large quantity of renewable electricity (that is not "available" in the CCU system, because this energy is required to run the CO_2 conversion process) the CCU full system only avoids emissions when the wider energy system (the electricity network) cannot do anything with this renewable energy [11]. Many CCU studies refer to the value of the CCU system to stabilize the electric power picks and valleys in the electricity network, but it should be noted that this is incompatible with standard CCU plants, based on catalytic hydrogenation of CO_2 to produce e.g. methane or methanol. These are complex chemical plants designed for a rather steady state supply of electricity and/or hydrogen, and will therefore require some kind of management of the electricity network to accommodate variability of renewable power. Alternatively, hydrogen buffering in storage tanks has been proposed as means of stabilizing the hydrogen supply, which incurs in additional costs to the process [12]. New generation CCU plants, based on electrochemical processes, are being conceived for intermittent operation, and could be used to store excess power in the form of CO_2-based fuels [13]. Also note that, in the case of the cement industry, it is impossible to close the carbon loop by redirecting the renewable power to the cement plant, since we are only representing in Figure 17 carbon emissions from a net flow of carbon coming from the underground (Carbon in $CaCO_3$), that cannot be allowed to grow towards an infinite large closed carbon loop.

The previous carbon balances indicate that CO_2 conversion to fuels (or other chemicals with a short life) may have limited effects for climate change mitigation or may even be

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counterproductive if deployed on a large scale. In contrast, CCS applied directly on the cement plant (Figure 18, left) or indirectly through negative emission technologies (also involving permanent CO_2 storage as noted in Figure 18, right) seem to be the only option to sustain cement manufacturing processes as we know them today. More detailed balances, applied to the cement industry, are presented above in Section 4.2. There we show that combinations of utilization and storage options, leading to integrated CCUS chains, where a limited amount of CO_2 is used for products that have a market, may be the best alternative for achieving maximum CO_2 avoidance at minimum cost.

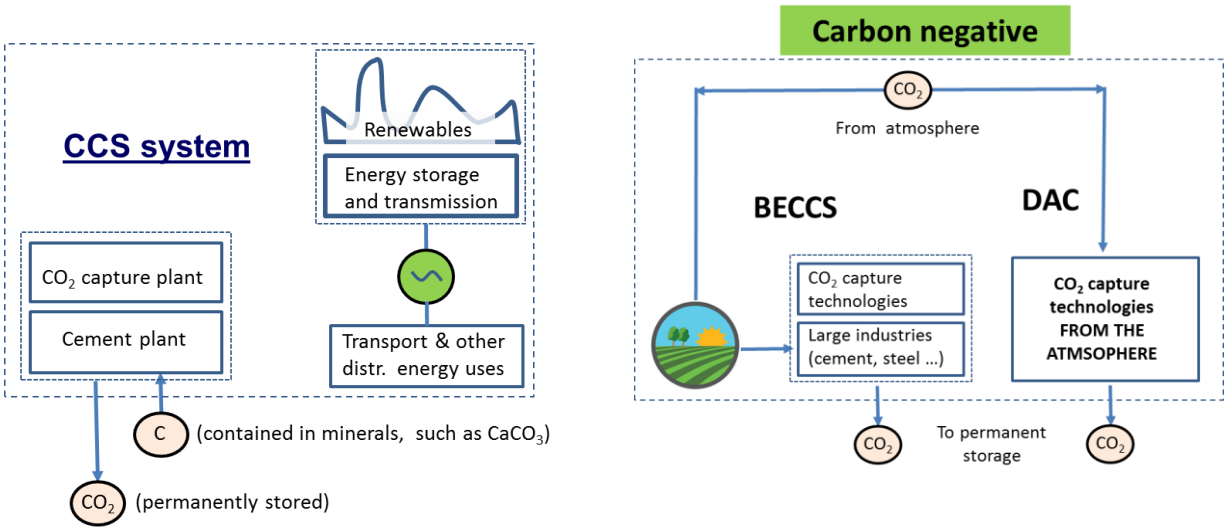

Figure 18 Schematics of a CCS system applied to taclke directly the process emissions of a cement plant (left), or as a negative emission technology to offset those emissions by capturing CO_2 from the air or from biomass firing (right).

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C CEMCAP PUBLIC DELIVERABLES

CEMCAP researchers have published 27 public deliverable reports. These are listed below. A large number of researchers have contributed to these deliverables, and are listed in Appendix D. All public deliverables are uploaded to the CEMCAP community in Zenodo after they have been finally approved by INEA.

Deliverable number	Deliverable title	Appendix D numbering
D2.10	Case study of communication and public acceptance in the cement industry	1
D2.11	CEMCAP Strategic conclusions – progressing CO2 capture from cement plants towards demonstration	2
D2.13	Clinker cooler film	3
D3.2	CEMCAP framework for comparative techno-economic analysis of CO2 capture from cement plants	4
D4.1	Design and performance of CEMCAP cement plant without CO2 capture	5
D4.2	Design and performance of CEMCAP cement plant with MEA post combustion capture	6
D4.4	Cost of critical components in CO2 capture processes	7
D4.5	Retrofitability study for CO2 capture technologies in cement plants	8
D4.6	CEMCAP comparative techno-economic analysis of CO2 capture in cement plants	9
D5.1	Post-capture CO2 management: options for the cement industry	10
D6.1	Optimised operation of an oxyfuel cement plant	11
D7.2	Oxyfuel burner prototype performance tests	12
D7.3	Oxyfuel CFD burner and large kiln simulations	13
D8.1	Status Report on Calciner Technology	14
D8.2	Oxyfuel suspension calciner test results	15
D8.3	Assessment of calciner test results Revision 1	16
D9.2	Analysis of oxyfuel clinker cooler operational performance	17
D10.3	Chilled Ammonia Process (CAP) optimization and comparison with pilot plant tests	18
D10.4	Feasibility study for CAP Process scale-up	19
D11.2	Experimental investigation of CO2 liquefaction for CO2 capture from cement plants	20
D11.3	Membrane-assisted CO2 liquefaction for CO2 capture from cement plants	21
D11.4	Membrane-assisted CO2-liquefaction scale up to TRL7-8	22
D12.1	Results from 30 kWth CaL CFB experiments	23
D12.2	Results of entrained flow carbonator/ calciner tests	24
D12.3	Calcium Looping CO2 capture for the cement industry – Demonstration of fluidized bed CaL at 200 kW scale and research on entrained flow CaL	25
D12.4	CaL reactor modelling and process simulations	26
D12.5	Design of post combustion capture and integrated calcium looping cement plant systems	27

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D ACKNOWLEDGEMENT OF CEMCAP RESEARCHERS

The research and innovations in CEMCAP would not have been possible to realise without the dedicated contributions from a large number of people from the different partners in the consortium. The contributors to the public CEMCAP deliverrables are listed below, with reference to what deliverables they have contributed to.

Family name	First name(s)	Affiliation	Contributions to (see Appendix 0
Abanades	Carlos	CSIC	2,23,24,25
Alonso	Mónica	CSIC	23,24
Anantharaman	Rahul	Sintef Energy Research	4,6,7,9,11
Arias	Borja	CSIC	23,24,25
Augustsson	Ola	GE-SE	19
Aursland	Karoline	Sintef Energy Research	1
Bakken	Jørn	Sintef Energy Research	13
Becker	Simon	IKN GmbH	3,14,17
Berstad	David	Sintef Energy Research	2,4,8,9,20,21,22
Bharadwaj	Hariharan Subrahmaniam	ETH Zurich	10
Bugge	Mette	Sintef Energy Research	13
Böhm	Matthias	VDZ gGmbH	17
Calvo	José Francisco Pérez	ETH Zurich	9,10,18
Campanari	Stefano	Politecnico di Milano	5
Carrasco	Francisco M.	IFK, University of Stuttgart	12,13
Cinti	Giovanni	C.T.G SPA / Italcementi	2,4,5,7,14,15,16,27
Consonni	Stefano	Politecnico di Milano	5
de Jong	Ardjan	TNO	10
De Lena	Edoardo	Politecnico di Milano	4,7,9,26,27
Degtyaruk	Yulia	VDZ gGmbH	3
Ditaranto	Mario	Sintef Energy Research	13
Feenstra	Maartje	TNO	10
Fleiger	Kristina	VDZ gGmbH	5,11,14
Fu	Chau	Sintef Energy Research	6,7,9
Gardarsdottir	Stefania Osk	Sintef Energy Research	2,7,9
Gatti	Manuele	Politecnico di Milano	4,5
Gazzani	Matteo	ETH Zurich	4,18
Goetheer	Earl	TNO	10
Grathwohl	Simon	IFK, University of Stuttgart	12
Grubbström	Jörgen	GE-SE	19
Hoenig	Volker	VDZ gGmbH	2,3,8,11,17
Hoppe	Helmut	VDZ gGmbH	4,5,7,8,10
Hornberger	Matthias	University of Stuttgart	2,25

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Lindemann Lino	Marco	VDZ gGmbH	3,17
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Mack	Alexander	University of Stuttgart	15,16
Maier	Jörg	IFK, University of Stuttgart	12,15,16
Marbán	Gregorio	CSIC	23,24
Martinez	Isabel	Politecnico di Milano	4,5
Mathai	Robert	IKN GmbH	3,14,17
Mazzotti	Marco	ETH Zurich	18
Monteiro	Juliana Garcia Moretz-Sohn	TNO	2,4,10
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Spinelli	Maurizio	Politecnico di Milano	4,5,7,26,27
Spörl	Reinhold	University of Stuttgart	25
Stallmann	Olaf	GE-SE	7,9
Stang	Jacob	Sintef Energy Research	22
Steenstrup-Duch	Anne	Sintef Energy Research	3
Størseth	Sigmund	Sintef Energy Research	2,3,4
Sutter	Daniel	ETH Zurich	2,8,9,18,19
Trædal	Stian	Sintef Energy Research	20,21,22
Turrado	Sandra	CSIC	23,24,25
Van der Meer	Rob	HeidelbergCement	2
van Os	Peter	TNO	4,10
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Wilms	Eike	thyssenkrupp Industrial Solutions AG	12,13

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E LIST OF CEMCAP PUBLICATIONS

List of published and submitted papers per November 25, 2018.

E.1 Peer-reviewed papers

Alonso, Mónica, Yolanda Álvarez Criado, José Ramón Fernández, and Carlos Abanades. 2017. "CO2 Carrying Capacities of Cement Raw Meals in Calcium Looping Systems." *Energy and Fuels* 31 (12): 13955–62. doi:10.1021/acs.energyfuels.7b02586.

Alonso, Mónica, Mathias Hornberger, Reinhold Spörl, Günter Scheffknecht, and Carlos Abanades. 2018. "Characterization of a Marl-Type Cement Raw Meal as CO2 Sorbent for Calcium Looping." *ACS Omega* 3 (11): 15229–34. doi:10.1021/acsomega.8b01795.

Arias, Borja, Mónica Alonso, and Carlos Abanades. 2017. "CO2 Capture by Calcium Looping at Relevant Conditions for Cement Plants: Experimental Testing in a 30 KWth Pilot Plant." *Industrial and Engineering Chemistry Research* 56 (10): 2634–40. doi:10.1021/acs.iecr.6b04617.

Carrasco, Francisco, Simon Grathwohl, Jörg Maier, Johannes Ruppert, and Günter Scheffknecht. 2019. "Experimental Investigations of Oxyfuel Burner for Cement Production Application." *Fuel* 236: 608–14. doi:10.1016/j.fuel.2018.08.135.

Lena, E. De, M. Spinelli, I. Martínez, M. Gatti, R. Scaccabarozzi, G. Cinti, and M. C. Romano. 2017. "Process Integration Study of Tail-End Ca-Looping Process for CO2 Capture in Cement Plants." *International Journal of Greenhouse Gas Control* 67: 71–92. doi:10.1016/j.ijggc.2017.10.005.

Pérez-Calvo, J.-F., D Sutter, M Gazzani, and M Mazzotti. 2018. "Pilot Tests and Rate-Based Modelling of CO2 Capture in Cement Plants Using an Aqueous Ammonia Solution." *Chemical Engineering Transactions* 69 (i): 145–50. doi:10.3303/CET1869025.

Spinelli, Maurizio, Isabel Martínez, and Matteo C. Romano. 2018. "One-Dimensional Model of Entrained-Flow Carbonator for CO2 Capture in Cement Kilns by Calcium Looping Process." *Chemical Engineering Science* 191: 100–114. doi:10.1016/j.ces.2018.06.051.

Turrado, Sandra, Borja Arias, Jose Ramon Fernandez, and Carlos Abanades. 2018. "Carbonation of Fine CaO Particles in a Drop Tube Reactor." *Industrial & Engineering Chemistry Research* 57 (40): 13372–80. doi:10.1021/acs.iecr.8b02918.

E.2 Papers published in conference proceedings

Bouma, Richard, Frank Vercauteren, Peter Van Os, Earl Goetheer, David Berstad, and Rahul Anantharaman. 2017. "Membrane-Assisted CO2Liquefaction: Performance Modelling of CO2Capture from Flue Gas in Cement Production." In *Energy Procedia*, 114:72–80. doi:10.1016/j.egypro.2017.03.1149.

Carrasco-Maldonado, Francisco, Jørn Bakken, Mario Ditaranto, Nils E.L. Haugen, Øyvind Langørgen, Simon Grathwohl, and Jörg Maier. 2017. "Oxy-Fuel Burner Investigations for CO2 Capture in Cement Plants." In *Energy Procedia*, 120:120–25. doi:10.1016/j.egypro.2017.07.160.

Hornberger, M., R. Spörl, and G. Scheffknecht. 2017. "Calcium Looping for CO2 Capture in Cement Plants - Pilot Scale Test." In *Energy Procedia*, 114:6171–74.

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doi:10.1016/j.egypro.2017.03.1754.

Johannes Ruppert, Helmut Hoppe, Volker Hoenig, Martin Schneider. 2017. “State-of-the-Art Paper No. 6: Carbon Capture and Storage (CCS): Long-Term Perspective for Application in the Cement Industry.” In *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead; CSI/ECRA-Technology Papers 2017*, 26–29. Düsseldorf, Germany: ECRA - European Cement Research Academy GmbH. http://www.wbcsdcement.org/pdf/technology/CSI_ECRA_Technology_Papers_2017.pdf.

Jordal, Kristin, Mari Voldsund, Sigmund Størset, Kristina Fleiger, Johannes Ruppert, Reinhold Spörl, Matthias Hornberger, and Giovanni Cinti. 2017. “CEMCAP - Making CO2 Capture Retrofittable to Cement Plants.” In *Energy Procedia*, 114:6175–80. doi:10.1016/j.egypro.2017.03.1755.

Mónica Alonso, Borja Arias, Alberto Méndez, Fernando Fuentes, J.Carlos Abanades. 2017. “Screening CO2 Capture Test for Cement Plants Using a Lab Scale Calcium Looping Pilot Facility.” In *Energy Procedia*, 114:53–56. doi:10.1016/j.egypro.2017.03.1146.

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Roussanaly, Simon, Chao Fu, Mari Voldsund, Rahul Anantharaman, Maurizio Spinelli, and Matteo Romano. 2017. “Techno-Economic Analysis of MEA CO2 Capture from a Cement Kiln - Impact of Steam Supply Scenario.” In *Energy Procedia*, 114:6229–39. doi:10.1016/j.egypro.2017.03.1761.

Spinelli, M., I. Martínez, E. De Lena, G. Cinti, M. Hornberger, R. Spörl, J.C. Abanades, et al. 2017. “Integration of Ca-Looping Systems for CO2 Capture in Cement Plants.” *Energy Procedia* 114 (November 2016). The Author(s): 6206–14. doi:10.1016/j.egypro.2017.03.1758.

12 CEMCAP papers will be published after GHGT-14, either in the conference proceedings or in a special issue of International Journal of Greenhouse Gas Control. Also several preer-reviewed papers are foreseen to be published in 2019. All papers will have the CEMCAP acknowledgement including the grant agreement number 641185.

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