Brage Rugstad Knudsen and Kristin Jordal, Sintef Energy Research, and Johannes Ruppertand and Volker Hoenig, VDZ gGmbH, discuss how to reduce CO$_2$ emissions in cement production.

**Introduction**
The importance of reducing manmade CO$_2$ emissions has been recognised by almost all countries worldwide through the signing of the Paris Agreement. Numbers vary between sources, but cement production is estimated to contribute 6 – 7% of global anthropogenic CO$_2$ emissions. More than 60% of these are process-related CO$_2$ emissions that result from the calcination of raw materials. This has given rise to the EU Horizon 2020-funded research project CEMCAP,
Sidebar 1. The CEMCAP consortium

Cement producers: HeidelbergCement, Germany; Italcementi, Italy; and Norcem, Norway.

Technology providers: thyssenkrupp, Germany; IKN, Germany; GE Power Sweden, Sweden; and Baker Hughes, a GE company, Germany.

R&D providers: SINTEF ER, Norway (project coordinator); ECRA, Germany; TNO, the Netherlands; ETH Zurich, Switzerland; University of Stuttgart, Germany; Politecnico di Milano, Italy; CSIC, Spain; and VDZ, Germany.

Sidebar 2. CCS technologies

There are several technologies under development or already developed for CO₂ capture from power plants. One post-combustion capture technology, amine absorption, is already implemented at commercial scale at the Boundary Dam coal-fired power plant in Saskatchewan, Canada. With this technology, CO₂ from an exhaust gas is absorbed in a circulating aqueous amine solution, and regenerated with steam. The same type of capture technology, but from a different technology provider, has also been selected by cement producer Norcem in Norway. Norcem is one of three industries that are currently potential candidates for CO₂ capture in the ongoing planning for a full-scale Norwegian CCS project.

where four different options for CO₂ capture from the cement kiln are investigated. In CEMCAP, expert cement producers and technology providers collaborate with researchers from universities and research institutions (Sidebar 1) to generate the knowledge and technology needed for the feasible implementation of CO₂ capture from cement production. In brief terms, capturing CO₂ means to separate concentrated CO₂ (95% purity or more) from a gas mixture, thereby enabling its compression or liquefaction for transport to a geological storage site. This CO₂ management chain is usually denoted with the abbreviation CCS: CO₂ capture and storage.

Governed by the laws of thermodynamics, all technologies for capturing CO₂ from any industrial or power-generating process, require energy. A key element in CEMCAP is therefore to compare and analyse the energy consumption for the investigated capture technologies. The majority of existing or envisaged CO₂ capture technologies have been developed with coal and/or natural gas-fired power plants in mind (Sidebar 2), a field where several of CEMCAP’s R&D partners have conducted cutting-edge research. CEMCAP capitalises on this knowledge, facilitating targeted development with a focus on advancing CO₂ capture technologies for retrofit of existing cement kilns.

CEMCAP investigation

CEMCAP investigates four different CO₂ capture technologies. One of the technologies is known as oxyfuel combustion capture. With this technology, combustion takes place in a CO₂/O₂ mixture instead of air, resulting in an exhaust stream with a particularly high CO₂ concentration. The three other capture technologies are different methods for post-combustion capture of CO₂. These end-of-the-pipe capture technologies allow for minimum changes in the traditional clinker production process in cement plants.

For advancing oxyfuel capture of CO₂ from cement kilns, operation of the clinker cooler, calciner, and the rotary kiln burner have been experimentally investigated and demonstrated at pilot scale in CEMCAP. The world’s first successful cooling of clinker under oxyfuel conditions has been demonstrated through a prototype oxyfuel cooler designed by IKN and installed at the HeidelbergCement plant in Hannover, Germany. VDZ, as a research partner, leads the testing with hot clinker and laboratory analysis of the clinker product. The oxyfuel pilot-scale clinker cooler is unprecedented in its innovative design, and the successful demonstration may be a game changer for oxyfuel operations in cement production. The tests with the clinker cooler prototype have been documented in a film that can be found on YouTube, or on the CEMCAP website.

A cement burner was tested under oxyfuel conditions in a 500 kW rig at the University of Stuttgart. The burner was designed by thyssenkrupp as a downscaled version of an industrial cement burner. These results were thereafter used for model validation and full-scale simulations of the burning process in the rotary kiln. Furthermore, the oxyfuel calcination was tested under relevant temperatures and residence times at University of Stuttgart, to verify the impact on calcination in an atmosphere with high CO₂ concentration. The CEMCAP experimental and analytical results will provide cement-kiln technology providers and cement-plant operators the necessary basis for a further scale up of the oxyfuel technology and deployment of oxyfuel processes in cement production.

The post-combustion capture technologies explored in CEMCAP are the Chilled Ammonia Process (CAP), Calcium looping (CaL) and Membrane-Assisted CO₂-Liquefaction (MAL). CAP is a proprietary technology of GE Power and close to commercialisation for coal and natural-gas power plants. The principle of CAP is similar to that of aqueous amine (Sidebar 2), but applies an ammonia-water solution for CO₂ capture instead of an aqueous amine solution.
As for amine capture, the energy consumed by the CAP comes from the steam-supply required for releasing absorbed CO$_2$. Transferring the CAP technology from power-plant flue-gas capture to cement kilns requires handling higher CO$_2$ concentrations than earlier implemented by GE.

GE Power in Växjö, Sweden, has accomplished pilot-plant test results with up to 35% CO$_2$ concentrations in a synthetic cement-kiln flue gas. Further research on operating conditions is conducted by researchers at ETH Zürich to minimise the energy consumption of the CAP.

**CaL technology**

Calcium looping (CaL) uses calcium oxide (CaO) particles to capture CO$_2$ from a flue-gas stream in a carbonator, forming limestone (CaCO$_3$). The CaCO$_3$ is thereafter calcined to CaO and ready for a new CO$_2$ capture loop. There is an obvious potential synergy between CaL and cement production in reusing purged CaO as feedstock in the kiln. Different options for integrating CaL into the kiln are being investigated by University Politecnico di Milano.

The high temperature required to drive fast calcination of CaCO$_3$ requires energy, which is obtained from fuel burnt inside the calciner. Furthermore, to avoid dilution of CO$_2$ released from the calciner, the fuel must be burnt with oxygen, not air, which means that the calciner operation is similar for the CaL and oxyfuel capture processes.

In addition, electric power is consumed for cryogenic distillation of O$_2$. The main focus of the CaL technology was originally CO$_2$ capture from coal-fired power plants. Integrating CaL in cement production requires adapting the carbonator to new operating conditions, including a higher CO$_2$ load, a more active sorbent, and smaller particle sizes. CEMCAP researchers have tested CaL under kiln-relevant conditions both in a 30 kW facility at CSIC and in one 30 kW and one 200 kW facility at the University of Stuttgart. With the earlier lack of industrial-scale testing of CaL under conditions relevant for cement production, these pilot experiments will provide a decision basis for future systematic process scale-up.

**Membrane-assisted CO$_2$-liquefaction**

CO$_2$ capture by MAL consists of two consecutive steps. The first step is bulk separation of CO$_2$ from flue gases using CO$_2$-selective polymeric membranes. This bulk-separation results in a sufficiently high concentration to enable the second step: a separation of liquid CO$_2$ through compression and cooling from the more volatile gas components.

Commercial and pre-commercial polymeric membranes have been tested in CEMCAP by TNO researchers, with the purpose of finding optimum separation rates for integration with the downstream CO$_2$ liquefaction. The MAL process requires electric power to drive compressors and vacuum pumps, i.e.
there is no requirement for fuel or process heat. Final preparations are currently taking place in the SINTEF laboratories for pilot-scale testing of CO₂ liquefaction in a 10 t CO₂/day research facility. These experiments will provide the basis for optimising the overall MAL process for flue gases with CO₂ concentrations that are of relevance for cement kilns.

Developing a framework for CO₂ capture

Based on the extensive analysis and experimental testing of oxyfuel and post-capture technologies, CEMCAP is now working towards establishing a techno-economic decision-basis to assess the energy requirements and to reduce the CO₂ capture cost in cement industries.

A milestone in this work is a framework document, publically available at the CEMCAP website, providing a common knowledge-basis for cement-plant operations, with input data for experimental and analytical research. This framework enables researchers to undertake consistent comparative techno-economic analyses, and is anticipated to be of relevance for CO₂ capture from cement production well beyond the project lifetime. The framework was established by CEMCAP research partners with Italcementi acting as industrial advisor.

CEMCAP interacts continuously with other research projects and communities that actively work on CO₂ capture related to cement. CEMCAP contributes to the ECRA CCS project through oxyfuel research activities, and also has a dialogue with the Norcem CCS project. This assures that the knowledge and expertise acquired from these different projects are united towards the common goal of low-emission cement production.

CEMCAP focuses efforts on communicating its results to a wide audience of both industries outside the consortium, academic communities, and to the public. Considering the high public focus on curbing CO₂ emission, CEMCAP believes that awareness of the activities and results will lift the cement industry in forefront of industrial CCS deployment.

The targets of CEMCAP are high. For all of the aforementioned capture technologies, an aim is a 90% CO₂ capture rate during tests under industrially-relevant environments for cement production. As cement plants differ significantly in structure, production characteristics, and location, there is no single, optimal one-size-fits-all capture technology. CEMCAP will end its work during the autumn of 2018 upon which pathways and perspectives for the anticipated most cost and resource effective options for CCS in the European cement industry will be concluded. The findings will be presented on 17 October 2018 in a public workshop.

About the authors

Brage Rugstad Knudsen is a Research Scientist at SINTEF Energy Research. He holds a PhD in Engineering Cybernetics from NTNU, the Norwegian University of Science and Technology. His main research interests are the modelling and optimisation of integrated energy systems. He currently works in the field of energy efficiency of industrial processes and CO₂ capture and storage.

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Volker Hoenig is Managing Director of the VDZ gGmbH at the Research Institute of the Cement Industry in Düsseldorf. He has more than 25 years experience in cement and lime processing technology. He is expert in thermal processing, energy efficiency, fuel substitution, cooler and preheater optimisation, as well as environmental technologies and climate protection.