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CO_2 Capture in the Cement Industry, Norcem CO_2 Capture Project (Norway)

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Abstract

The cement industry is a major emitter of anthropogenic greenhouse gas emissions and contributes to around 5% of the global CO_2 emissions. In Norway, Norcem is the only cement manufacturer and account for 2.5 % of the national emissions, due to different industrial structure compared to other countries. Until recently, CO_2 capture in Norway has focused primarily on emissions from offshore installations and gas power plants. There has been little focus on CCS in connections with land-based industrial emissions, although the number of sources is relatively large, with annual CO_2 emission totalling approximately 6 million tonnes. The demand for cement and concrete is expected to increase in the coming years. Therefore, the cement industry needs to be proactive in finding solutions which reduce its climate impact.

Norcem AS (Norcem) and its parent company HeidelbergCement Group (HeidelbergCement) have joint forces with the European Cement Research Academy (ECRA) to establish a small-scale test centre for studying and comparing various post-combustion CO_2 capture technologies, and determining their suitability for implementation in modern cement kiln systems. The small-scale test centre has been established at Norcem's cement plant in Brevik (Norway).

The project has received funding from Gassnova through the CLIMIT program. The project was launched in May 2013 and is scheduled to conclude in spring 2017 (Test Step 1). The project is being carried out on behalf of the European cement industry and managed by Norcem.

The project mandate involves testing of more mature post-combustion capture technologies initially developed for power generation applications, as well as small scale technologies at an early stage of development. The project does not encompass CO_2 transport and storage.

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Keywords: Cement Industry, Small-Sale Test Centre, Post-Combustion Carbon Capture Demonstration, Full-scale Perspective

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1. Introduction

The cement industry is a major source of industrial greenhouse gas emissions and contributes to around 5% of the global anthropogenic greenhouse gas emissions. In order to address the environmental imperative of climate change the International Energy Agency modelling indicates that the energy related CO_2 emissions have to be cut in half from the current levels by 2050. As part of this global reduction the IEAGHGT has estimated that, in a baseline scenario which includes today's policies and the forecasted market development, the cement industry will require to reduce its carbon emissions from 2,34 Gt to 1.55 Gt (i.e. 34%).

The cement industry has reduced its production related greenhouse gas emissions over the last decades through a variety of means. These include raw material substitution, fuel switching (utilization of alternative fuels and biomass) and reduction of the clinker to cement ratio among others. Modern cement plants operate today at or close to the theoretical limits of efficiency and deployment of carbon capture seems to be the only available technology to meet future global climate change goals.

CO_2 emission is an unavoidable by-product of the cement manufacturing process. The raw material (limestone) used in cement manufacturing account for roughly 2/3 of the total CO_2 emitted from the cement plant. The other 1/3 generally comes from the combustion of fossil fuels to obtain the heat required for the limestone decomposition process ($CaCO_3 \rightarrow CaO + CO_2$).

In order to evaluate the realism in deployment of carbon capture to mitigate the environmental impact, testing on real cement flue gas is required. One of the preferred techniques for capturing CO_2 in cement plants is post-combustion capture. Such technique is proven in some industries but to date, no cement plants utilize capturing technology to mitigate its CO_2 emissions.

Norcem AS (Norcem) and its parent company HeidelbergCement Group (HeidelbergCement) have joint forces with the European Cement Research Academy (ECRA) to establish a small-scale test centre for studying and comparing various post-combustion CO_2 capture technologies and determining their suitability for implementation in modern cement kiln systems. The small-scale test centre has been established at Norcem's cement plant in Brevik (Norway) and was commissioned and ready for testing in March 2014.

1.1. Norcem & HeidelbergCement

Norcem AS develops, manufactures, markets and sells all types of cement to the building, construction and oil industry in Norway. Norcem is the sole cement manufacturer in Norway and operates two plants, one in Brevik and one in Kjøpsvik. Both plants are among the most modern in Europe, also in terms of energy consumption and emissions. Norcem employ approximately 500 people.

HeidelbergCement has since 1999 been Norcem's parent company. Norcem is part of the business area Northern Europe (HCNE). HCNE operates six cement plants; two in Norway (Norcem Brevik and Norcem Kjøpsvik), three in Sweden (Cementa Slite, Degerhamn and Skövde) and one in the Estonia (Kunda). HCNE has a total cement production of approximately 5.5 million tonnes of cement.

HeidelbergCement Group is a German multinational building material company headquartered in Heidelberg, Germany. It is currently (as of 2010) the world's third largest cement producer, the market leader in aggregate and third in ready-mix concrete. The company employs some 53,000 people at 2,500 locations in more than 40 countries with an annual turnover of approximately EUR 11 billion.

1.2. ECRA

ECRA, the European Cement and Research Academy, was founded in 2003 as a platform upon which the cement industry supports, organizes and undertakes research activities in the context of the production of cement and its application in concrete. By creating and disseminating knowledge from research, ECRA's aim is to facilitate and accelerate innovation to guide the cement industry in the 21st century. ECRA is a Research Institute with members from European cement producers and is funded by its members.

On behalf of the cement industry in Europe, ECRA is mandated to examine the technical and economic feasibility of CO_2 capture technology as a potential application in the cement industry and in the Norcem CO_2

capture project; ECRA has a central role in technical supporting and dissemination of project results and outcomes.

Nomenclature

Clinker	Mediate product leaving the kiln which is milled with gypsum to make cement
ECRA	European Cement Research Academy
GSA	Gas Suspension Analyser (SO_x-Scrubber, Semi-dry lime injection scrubber)
IFK	Institut für Feuerungs- und Kraftwerkstechnik Universität, Stuttgart
MC	Membrane Consortium (DNV GL, NTNU & Yodfat Engineers)
MTU	Mobile Test Unit (Aker Solutions)
NanoGlowa	Project; Nano-membranes against GLObal WArming (www.nanoglowa.com)
RCC	Regenerative Calcium Cycle (Alstom)
RTI	Research Triangle Institute
SNCR	Selective Non-Catalytic Reduction using NH_3
TP	Technology Provider

2. Project Target and Scope

Up-until recently only a few feasibility studies have been conducted related to carbon capture on cement flue gases. The investigations have mainly been carried out through laboratory testing and simulation of real terms. In order to bring the development further, testing on real conditions at a cement plant is required, proving the realism of technology performance in a commercial scale perspective.

The project in Brevik aims to demonstrate capture of CO_2 from a cement plant. The objective is to acquire knowledge from various post-combustion capture technologies and assess the long term technology performance in a commercial scale perspective. A Benchmark Study will be conducted where the technologies will be compared and the suitability of implementation at modern cement kilns is to be determined.

A small scale test centre is established for demonstration of carbon capture technologies and the mandates involves testing of more mature capture technologies initially developed for power generation applications, as well as small scale technologies at an early stage of development. Four different capture technologies are being demonstrated in Test Step 1. The project does not encompass CO_2 transport and storage.

Carbon capture is energy demanding and one of the essential criterions for comparison of technologies is the energy use per ton CO_2 captured (avoided). At Norcem a considerably quantity of waste heat can be made available, therefore the capture technology's capability of utilizing this waste heat is of special interest.

In addition to the energy demand, important focus areas is the capture rate, performance impact from flue gas impurities, all cost aspects (capex, opex) and space requirement among others.

In an industry perspective, the Benchmark Study will be one of the main outcomes of the project, where knowledge regarding realism in industrial carbon capture and especially deployed in the cement industry will be revealed.

3. Pilot Testing

3.1. Test Centre Brevik

Three separate infrastructures are prepared at site; one main infrastructure for testing of more mature capture technologies and two smaller infrastructures for testing of capture technologies at an early stage of development. After Test Step 1, the infrastructures will in principle be available for testing of other capture technologies.

Four different post-combustion capture technologies are being studied in Test Step 1:

Table 1. Technologies demonstrated in Test Step 1.

Technology Provider	Technology	Maturity
Aker Solutions (NO)	Amine	1
Research Institute Triangle (RTI – US)	Solid Sorbent	3
DNV GL, NTNU & Yodfat Engineers	Membrane	3
Alstom Power	Regenerative Calcium Cycle	2

Due to lack of own test equipment, Alstom's regenerative calcium cycle (RCC) has been demonstrated utilizing a large scale pilot at the IFK Stuttgart (Germany).

Fig. 1 pictures the flue gas piping to the three infrastructures. The flue gas is supported the main infrastructure through an 8'' carbon steel piping and the distance from the flue gas stack to the test facility is around 150 m.

Fig. 1. Flue gas supply

3.2. Test Regime

In this project, slip streams of flue gas from the cement production together with other required utilities are provided the three capture facilities. After capture demonstration, the CO_2 is being released in a controlled way to the atmosphere. The cement flue gas is characterized with high CO_2 concentration (17-20 %). Moreover the flue gas is contaminated with SO_x, NO_x and dust. Norcem Brevik is equipped with both SO_x- and NO_x-scrubbing equipment which makes it possible to tailor the flue gas concentrations and simulate flue gases at other cement plants. The flue gas from Norcem Brevik is also characterized with large H_2O concentration of approximately 10%. This means that a considerably large amount of humidity has to be taken care of in a pre-treatment plant upfront the capture process. Bag house filter in combination with electrical precipitators keeps the dust content at a lower level of 5-7 mg/Nm^3.

Akers Solutions' MTU is installed at the main infrastructure for demonstration of the advanced amine technology, and the technologies by RTIs' and the Membrane Consortiums (MC) are being demonstrated using the small scale infrastructures.

Depending on which clinker is produced, the flue gas to be cleaned holds temperatures in the range of 85 – 105 °C to 150-180 °C, which means that the flue gas needs to be cooled down before capture. Acid components as SO_x and NO_x and dust particles are removed from the flue gas during the condensation together with large quantity of water. Table 2 illustrates the flue gas composition at Norcem Brevik.

Table 2. Flue gas Characterization, Norcem Brevik

Compound,	Concentration	Unit
H_2O[a]	11-15 / 15-18	%
SO_2[b]	0-30/ 100-450	mg/ Nm^3
HCl	< 10	mg/ Nm^3
NO_x[c]	180-250	mg/ Nm^3
O_2	9-12	mg/ Nm^3

a: Concentration dependent on clinker production and if the GSA is in operation or not

b: Dependent on limestone quality and if the GSA is in operation

c: Dependent on the SNCR, if it is in operation or not

3.3. Advanced Solid Sorbent Technology, RTI

The carbon capture technology from the US Research Triangle Institute (RTI) was installed in April 2014 and is a thermal-swing CO_2 capture process utilizing a high CO_2 capacity sorbent in a fluidized, moving-bed reactor arrangement. In Test Phase I, performance testing was conducted for three months, from April to June with the objectives to; 1) Evaluate the technology's economic feasibility for commercial-scale application within the cement industry, 2) Collect representative gas exposure data for the CO_2 capture sorbent and optimize the process for cement plant application, and 3) Demonstrate, on a pilot-scale, the technology's capacity to achieve effective and continuous mitigation of CO_2 from Norcem's cement plant.

Promising sorbent performance outcome has resulted in the decision to continue on to a Test Phase II in which a three-floor pilot will be used for long-term performance testing. Test Phase II has been launched and preparing of test pilot and test program is on-going. The Phase II testing is scheduled to run for a year, from spring 2015.

Fig. 2. RTI's bench-scale test unit used in Phase I together with the staff from RTI and Norcem

3.4. Advanced Amine technology

Aker Solutions is demonstrating its advanced amine technology using their mobile test unit (MTU). The unit was installed in April 2014 at the test centre's main infrastructure. The MTU is an advanced CO_2 capture pilot that has been operated by Aker Solutions since 2008 and used in previous testing projects for other industrial applications around the world. Aker Solutions has operated the unit for more than 20,000 hours and has conducted test campaigns in industrial environments, such as for the coal and gas power industry, refinery industry and now the cement industry. The MTU is equipped with a 40-metre-long absorber and a 14-metre regenerator. The flue gas is pre-conditioned before it enters the absorption column. The unit has a capture capacity of approximately 0.2 tonnes/ h and is operates 24–7.

The amine mixture demonstrated at Brevik has been specially developed to "fit" the cement flue gas and is the result of an extended optimisation programme conducted at the Tiller laboratory at SINTEF in Trondheim, Norway.

The test program was launched in May 2014 and will last until the end of October with the following main objectives; improve understanding of the 1) energy demand 2) possible amine degradation and 3) possible emissions (focus on degradation products).

Fig. 3. Aker Solutions MTU testing at Norcem Brevik

In general the test results after 4 months demonstration indicate that the MTU operates stable and well on the flue gas from the cement kiln. At basecase operation, the MTU is cleaning 450 sm^3/ h flue gas with 90 % CO_2 removal and with promising specific reboiler duty. Results so far indicate as well low consumption of amine, low degradation and low formation of nitrosamines and nitramines.

3.5. Membrane Technology

The three partners DNV GL, NTNU and Yodfat Engineers have joint forces to develop a membrane technology for cement application. In the project 1) DNV GL is responsible for the modelling and holds the partner coordination role, 2) the Norwegian University of Science and Technology (NTNU) is responsible for the membrane production and is carrying out the planned test programme and 3) Yodfat Engineers, an Israeli engineering company, is responsible for the design and construction of the test pilot.

A one stage membrane module is deployed where handmade poly-vinyl-amine based, fixed-site carrier membranes, produced as flat sheets, placed in 12 cassettes inside the membrane module (two sheets in each cassette). The total membrane area is approximately 1.5 m^2. A 6 months test program is defined in Test Phase I with the objective to conduct long term exposure testing and demonstrate a CO_2 recovery in the range of 60-70 % (same results obtained in a former project; "NanoGlowa" "where the membrane where deployed on flue gas from power plants).

The test pilot was installed during spring 2014 and performance testing has been on-going since May and will continue to the end of October. After 4 months testing, the test results indicate that the membranes withstand the cement flue gas environment without being damaged in addition to promising CO_2 recovery results, in the range of target.

Fig. 4. a) DNV GL, NTNU & Yodfat Engineers Membrane Test Container b) The Membrane Unit

3.6. Regenerative Calcium Cycle, RCC

Alstom Power is conducting a one-year de-risking study of its regenerative calcium cycle technology (RCC). This technology uses processed limestone to capture CO_2 from the flue gas, deploying a calciner/carbonator system to facilitate the reactions. Alstom is not the owner of a test pilot; therefore the test facility at the Institute of Combustion and Power Plant Technology (IFK) at the University of Stuttgart is used for performance testing. The objective of the de-risking study is to remove show stoppers and prepare the basis for the development of a larger test pilot which might be used for future performance testing in real cement flue gas applications. Two test campaigns (1 week each at 24/7 operation) using limestone from e.g. Verdal, Norway have been successfully conducted during spring 2014 and data for closing the material and energy balances are collected. The data is currently being assessed to model a larger scale system and to indicate a commercial scale design. The project will be concluded by the end of 2014.

4. Benchmark Study

The four carbon capture technologies studied in this project are at various stage of development, which makes the commercial scale comparison challenging. In order to compare apples with apples a Benchmark Study is defined and will be conducted with input from the technology providers (TP). A material- and energy balance approach is established where the TP's are asked to give input on all energy- and material streams, up- and down-streams their capture plant. Other relevant information as costs (capex & opex), HSE-issues and space requirements are questioned as wells. Fig. 5 illustrates the balance approach which will be basis for the comparisons of technologies and assessment of their suitability for implementation at modern cement kiln systems.

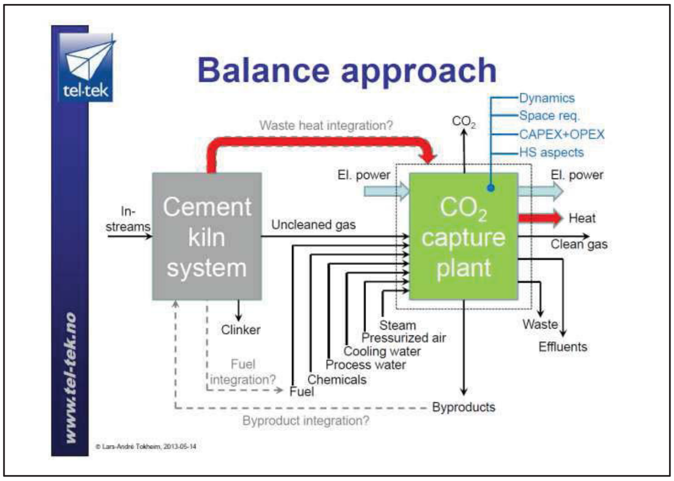

Fig. 5. Benchmark Study Balance Approach

Depending on the future deployment of the product CO_2 gas (storage, reuse), the characteristics (purity) of the captured gas is of importance. Quality requirements are not defined in this project as the mandate only involves demonstration of the capture performance. The CO_2 product gas quality will however be registered for later assessment.

5. Energy Consumption, Utilization of Waste Heat

As carbon capture technologies are known to be energy demanding, full capture (100 %) will need a separate power plant to provide the energy needed for capture. In order to save especially costs (CAPEX & OPEX), the capture technologies capability of utilizing waste heat is therefore of special interest to the cement industry. A cost- benefit analysis utilizing the waste heat potential will be thoroughly assessed in the Benchmark Study.

Calculations indicate that the waste heat potential at Norcem Brevik is approximately 22-24 MW, which is a considerably higher potential compared to other cement plants in Europe. Waste heat is often used to dry the raw materials and since the raw materials at Norcem Brevik are relatively dry, more waste heat might be made available for a potential capture plant. This waste heat might be used as regeneration energy in a stripper section of a CO_2 capture plant, which will reduce the investment and operational costs of a CO_2 capture plant.

If waste heat is being utilized through capturing (replacing the existing condition towers with waste heat boilers), the key question is how much CO_2 is the technology capable to capture utilizing this amount of energy? Calculations conducted for the Brevik plant indicates that with a traditional amine technology (using traditionally MEA), approximately 30-40 % of the CO_2 might be captured, which correspond to 300- 400 0000 tonnes CO_2/ year. As Norcem Brevik has a considerably large waste heat potential, a capture plant operated only with energy support from waste heat is of interest. A study conducted by ECRA and Norcem has revealed that the situation in Brevik is rather unique and that other cement manufacturers don't have this large waste heat potential.

5.1. Commercial Capture Scale Design

The capture technologies energy requirement is important part of the commercial scale designs evaluation; however ref. the Benchmark Study, many other factors needs to be accounted to give a complete overview of a possible optimal capture plant size and design. Technical, environmental and economic aspects need to be considered and even local conditions at the cement plant and its surroundings might be crucial for the design. A set of benchmark indicators is defined to make the comparison of technologies and evaluation of commercial scale design possible. All premises and assumptions made will be carefully described in the Benchmark Study.

Three different cases will be especially assessed and where the technology providers will give their input:

- Case 1 (reference): Full-size (minimum 85 %) cleaning, no waste heat available
- Case 2: Full-size (minimum 85 %) cleaning, waste heat available as per Norcem Brevik
- Case 3: Reduced –size cleaning, based on a cost-optimal utilization of waste heat at the Brevik plant. In this case the TP will decide which capture ratio is cost-optimal

In elucidation of the above discussions, it might turn out that the optimal commercial capture scale design for mitigation of carbon emissions from cement plants differ from the traditional thinking of 100 % capture.

6. Summary

Norcem AS (Norcem) and its parent company HeidelbergCement Group (HeidelbergCement) have joint forces with the European Cement Research Academy (ECRA) to establish a small-scale test centre for studying and comparing various post-combustion CO_2 capture technologies, and determining their suitability for implementation in modern cement kiln systems. The small-scale test centre has been established at Norcem's cement plant in Brevik (Norway).

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The project in Brevik aims to demonstrate capture of CO_2 from a cement plant. The objective is to acquire knowledge for various post-combustion capture technologies and assess the design of and long term technology performance in a commercial scale perspective. A benchmark study will be conducted where the technologies will be compared and the realism of implementation at modern cement kiln systems is to be determined.

A small scale test centre is established for demonstration of various post-combustion carbon capture technologies and four different capture technologies are being demonstrated in Test Step 1.

Technologies demonstrated in Test Step 1.

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The capture technologies energy requirement is important part of the commercial scale designs assessment; however, many other factors needs to be accounted to give a complete overview of a possible optimal capture plant size and design. Technical, environmental and economic aspects need to be considered and even local conditions at the cement plant and its surroundings might be crucial for the design. A commercial scale design might involve lower carbon capture rate than the traditional 100% scenario.

Most of the planned pilot testing in Test Step I will be completed within 2014; both Aker Solutions and the Membrane Consortium will complete their test programs within Oct 2014. Alstom has completed their testing and will conclude in Nov 2014. RTI has finalized their Phase I program and the performance outcome has resulted in the decision continuing into a test Phase II, which involves long term testing with a larger test pilot.

Results and findings from the field testing will be used as input to the Benchmark Study which will issue its first draft during spring 2015. This means that before summer 2015 Norcem, HeidelbergCement and ECRA will have much more knowledge regarding the realism of industrial carbon capture and especially in the cement industry.

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