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Abstract

The Chilled Ammonia Process has been developed by General Electric Power for the power plant application up to a level of Technical Readiness Level of 7 (TRL 7) before entering the CEMCAP project. This report explains the efforts made for reaching this level. It also briefly describes efforts in the CEMCAP to reach to a high TRL of 6 for cement application and how this would be implemented in a cement plant. Finally, it also defines the efforts required to reach TRL of 7 and beyond for also cement application.

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1 EXECUTIVE SUMMARY

GE has a vast experience of the Chilled Ammonia Process (CAP) for capturing CO_2 from a power plant. In this field of application GE has reached the Technology Readiness Level (TRL) of 7, defined within CEMCAP. This TRL, which is described in this report, means **“**System prototype demonstration in operational environment”

.

When entering the CEMCAP it was identified that the major difference for CAP between a cement plant and a coal-fired power plant is the higher CO_2 concentration in the flue gas, leading to some uncertainty on how the process needs to be adapted to best cope with the higher CO_2 concentration.

Within CEMCAP, this major reason for uncertainty has been explored with very favorable results by running an extensive test program in the GE Technical center facilities in Växjö. These tests in combination with Aspen Plus process simulation has enabled further improvements of the energy consumption for the process as well as minimizing the height of the absorption columns. The budget for these experimental activities in Växjö has been €560,000 and for ETHZ work CHF 700,000.

The expected consumption numbers for the emissions of 100 ton of CO_2/h for a “standard cement plant” of 1,000,000 tons of clinker a year is 2.37 MJ of steam/kg CO_2 (58 MW), which is a very attractive number.

For the CAP to be accepted on TRL of 7 the following must be fulfilled:

- System prototype demonstration in operational environment (with clinker quality maintained).
- For end-of-pipe technologies this means a full prototype operated with flue gas from operational cement kiln.
- For technologies that are highly integrated with the cement kiln, this means a prototype where all critical sub-systems are fully integrated.

GE has all these aspects fulfilled for the *power* application. However, the gases even if it on paper seems to be very similar, have not been operated in full scale for a cement application. The major difference between flue gas originating from a cement plant and a power plant is the CO_2 concentration, but minor contaminants may also differ. This difference in CO_2 concentration, and also SO_2 concentration, has been extensively tested in the CEMCAP project and has been proven not entailing any difficulties.

To be accepted for TRL of 6 the following must be fulfilled:

- Technology demonstrated in environment relevant to operation in cement kilns (conditions replicating industrial operation) with clinker quality maintained. Trace elements should be included in flue gas if relevant.
- Demonstration of the sub-systems affected by the cement conditions may be sufficient if the full system is demonstrated at TRL 6 or higher for other applications (e.g. power plants).

GE is fulfilling all these aspects for TRL of 6 for the *cement* application.

To reach TRL 7 also for the cement application building a larger pilot or demonstration plant of at least 100,000 ton/a would be required. GE has the full EPC capability for executing such a project.

GE’s requirements for doing so for the cement application are linked to:

i) To which extend the engineering efforts can be funded by developer or institutions
ii) What are the chances to get such opportunity(ies) materializing?
iii) The expected possibility of getting our costs covered

Steam is normally not available at a cement plant. In this report an investigation has been performed to build a biomass boiler for the steam and electricity supply at the site capturing also these emissions. Such an arrangement would result in **negative emissions** of CO_2 of total 20 ton/h with a boiler power of 84 MW.

If building the CAP unit and a biomass combined heat and power plant would:

- Make the CCS+Boiler and the cement plant to a negative emitter of CO_2 unit of -160,000 ton/a (instead of 800,000 ton/a emitter)
- Make it a net producer of electricity.
- Consume about 675 GWh/a of biomass corresponding to 140,000 tons/a of CO_2.

GE has the capability to build a full-size EPC contract for a CAP unit including the boiler. GE are prepared to do so based on our previous experience and present capabilities.

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2 INTRODUCTION

Globally, concrete is the second most used commodity after water, and its use is expected to increase with increased urbanization.

With concrete however, comes a challenge for climate protection: Cement is a main constituent of concrete, and its production currently generates approximately 7 % of man-made CO_2 emissions.

The CO_2 generation is an inherent part of the cement production process, due to the calcination of the most important raw material, limestone: about 60 % of the CO_2 emissions from cement production are due to this conversion, whereas 40 % come from the burning of fuels (which are to a large extent fossil) to provide heat.

Energy efficiency measures and use of renewable fuels can therefore only reduce a part of the CO_2 emissions.

2.1 Background

CEMCAP is a project funded by the EUs Horizon 2020 project on CO_2 capture from cement production.

- Starting date: May 1st 2015
- Project duration: 42 months
- Budget: €10 million
- EU contribution: €8.8 million
- Swiss government contribution: CHF 700,000
- Number of partners: 15

The CEMCAP project consists of twelve work packages (WP) that are grouped in four sub-projects (SP) and coordinated by: SINTEF Energy Research, Norway.

The CEMCAP work have included:

- A framework for the research to be conducted, based on the existing framework from the European Benchmarking Task Force (EBTF) in combination with a reference cement plant previously defined by European Cement Research Academy (ECRA).
- A comparative techno-economic analysis undertaken by all CEMCAP CO_2 capture technologies, compared with a reference case using MEA (Mona-Ethanol-Amine) as capturing media.
- The CO_2 capture technologies included in the CEMCAP project:
    - Oxyfuel, retrofit (key oxyfuel components such as burner, calciner and clinker cooler has been tested independently, corresponding to reaching TRL of 6).
    - The Chilled Ammonia Process, post-combustion.
    - Membrane-assisted CO_2 liquefaction, post-combustion.
    - Calcium Looping, post-combustion.

GE joined the project and their CAP pilot plant at the GE Technical Center in Växjö, Sweden, was to the project disposal for performing tests. The experimental work was carried out in close collaboration with the ETH Zürich (ETHZ), also responsible for modeling, simulation and

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optimization work for CAP. The generated experimental data has then served as an input for building an optimized simulation model for the CAP for a cement plant (carried out by ETHZ) and is documented in deliverable D10.3.

2.2 Limitations

The work in CEMCAP has been restricted to the technology of separating the CO_2 from the emitted gases.

- After this stage comes a compression stage in order to get “storage” quality.
- Then the CO_2 needs to be transported safely to a location for storage
- If not transported through pipelines the CO_2 will also require an intermediate storage
- A method of filling and emptying the vessel of transportation will also be required
- Then the injection and the storage are also important items

All above items have not been a part of CEMCAP project but needs to be addressed in the future.

In order to introduce CCS in a large scale also the public acceptance for all above items need to be discussed and addressed. Nether this has been in the scope of the CEMCAP project.

Finally, CCS comes with a cost. Implementing the technic in a *single* cement plant would increase the cost of producing the cement and make it difficult to compete with cement produced with CO_2 emissions. How to politically solve this issue has not neither been in the scope of in CEMCAP project.

2.3 Technology readiness levels (TRL)

Technology Readiness Levels (TRLs) are indicators of the maturity level of particular technologies. This measurement system provides a common understanding of technology status and addresses the entire innovation chain. There are nine technology readiness levels within CEMCAP; TRL 1 being the lowest and TRL 9 the highest.

Table 1: TRL definitions for CO_2 capture from cement kilns used within CEMCAP.

TRL	Horizon 2020	CEMCAP: CO_2 capture from cement kilns	
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).	Actual system proven in operational cement kiln (with clinker quality maintained), and competitive manufacturing of full system. Technology is commercially available for cement producers.	Full commercial application
8	System complete and qualified.	System complete and qualified in operational cement kiln (with clinker quality maintained). First of a kind commercial system is installed and works.	Demonstration
7	System prototype demonstration in operational environment.	System prototype demonstration in operational environment (with clinker quality maintained). For end-of-pipe technologies this means a full prototype operated with flue gas from operational cement kiln. For technologies that are highly integrated with the cement kiln, this means a prototype where all critical sub-systems are fully integrated.	Pilot
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).	Technology demonstrated in environment relevant to operation in cement kilns (conditions replicating industrial operation) with clinker quality maintained. Trace elements should be included in flue gas if relevant. Demonstration of the sub-systems affected by the cement conditions may be sufficient if the full system is demonstrated at TRL 6 or higher for other applications (e.g. power plants).	
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).	Technology validated in environment relevant to operation in cement kilns (conditions replicating industrial operation). Trace elements should be included in flue gas if relevant. Validation of critical sub-systems is sufficient.	Small pilot
4	Technology validated in lab.	Technology validated in lab (continuously operated).	Lab/bench
3	Experimental proof of concept.	Experimental proof of concept.	
2	Technology concept formulated.	Technology concept formulated.	Concept
1	Basic principles observed.	Basic principles observed.	

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The following reasoning lies behind the formulations:

- *Level of integration:* For TRL 7-9 CEMCAP description refers to "system". This is understood as the complete system with all critical sub-systems successfully integrated, and where the capture system is not affecting the operability of the plant in a negative way. For TRL 4-6 the description refers to "technology", and not "system". Here it is enough to demonstrate/validate the relevant sub-systems, depending on the knowledge about the full system, for instance from previous testing of the full system for other applications.
- *Clinker quality:* Maintained clinker quality is an important aspect for CO_2 capture from cement kilns. The criteria have been set that it must be shown that clinker quality is maintained from pilot scale and up (TRL 6 and up). This is not relevant for typical end-of-pipe technologies.
- *Relevant environment:* The description refers to "relevant environment". For some technologies it is critical to investigate the effect of certain trace elements in the cement flue gas, and in these cases such elements should be included for the flue gas to be classified as "relevant environment" (TRL 5 and 6).
- *Scale:* It has no been set limits regarding sizes of the experimental facilities, since the importance of this depends on the technology. For instance, for the integrated entrained flow calcium looping process, the size of the experimental facility is important since solids lifting becomes more challenging when riser diameter is increased. For membranes, on the other hand, size is not so critical once one module is tested under realistic conditions, since the technology is scaled up by increasing the number of modules. Also, some technologies have already been demonstrated on large scale for other applications than cement, and then the size of the test facility for the cement application is of less importance. For technologies where scale is important, the following can be used as guidelines): TRL 9: full scale cement plant; TRL 8: 10-100% of full scale; TRL 7: 1-10%; TRL 6: 0.1-1%; TRL 5: <0.1%.
- *Length of operating time:* For a cement kiln the possibility for continuous operation is essential, and this aspect is therefore of importance for higher TRLs. However, we have not set clear limits regarding operating time since this is included implicitly in the definitions. For instance, it is highly unlikely that a first of a kind commercial system (TRL 8) will be installed in a cement kiln unless long term operability already is proved.

3 THE CHILLED AMMONIA PROCESS (CAP) IN POWER APPLICATION

3.1 General description

The main sections of the CAP are shown in figure 1, as well as the objective of the different unit operations are described below:

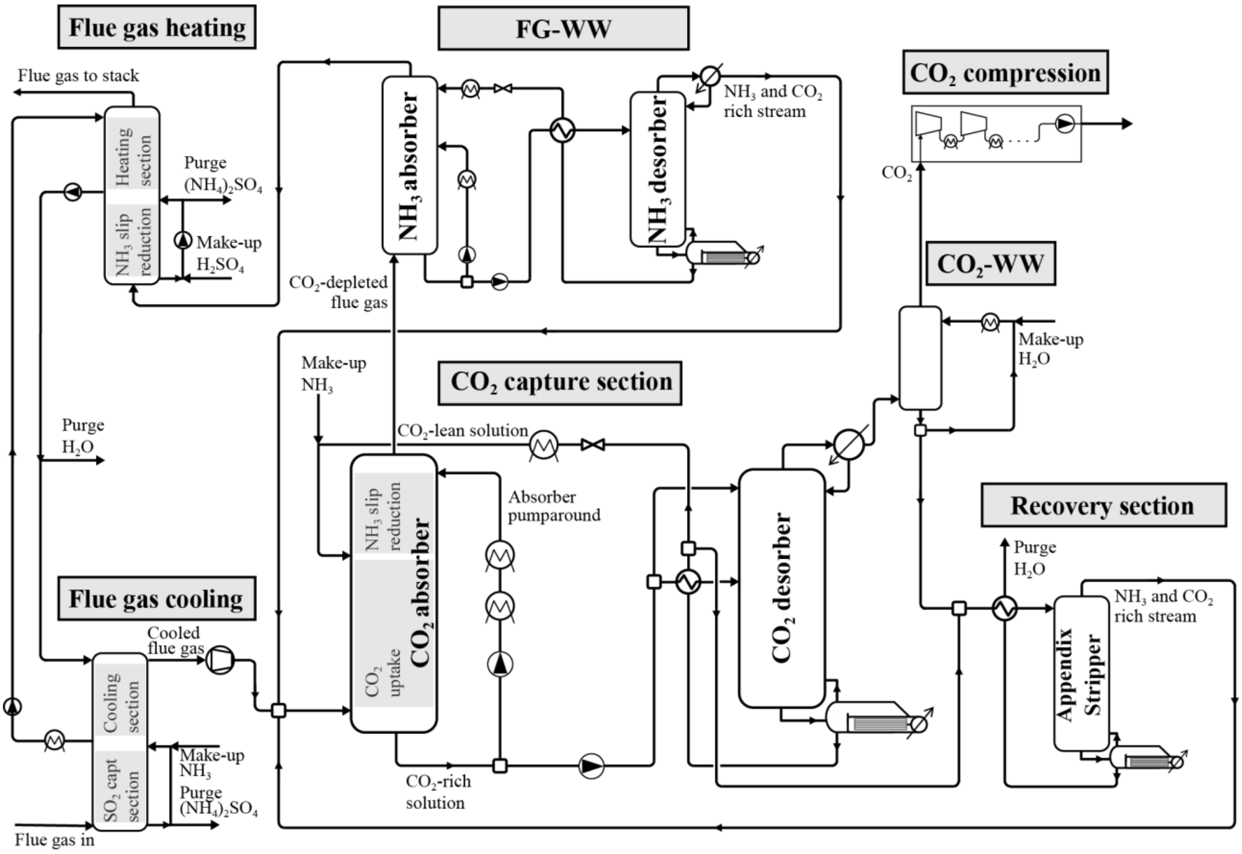

Figure 1: Simplified flow scheme of the CAP.

1. **Flue gas cooling**. The CO_2 rich gases from the cement factory first enter the Direct Contact Cooler (DCC), in which the flue gas is conditioned to have a very low SO_2 content. SO_2 should be removed to preferable less than 1 ppm. If not, SO_2 will react with the ammonia in the CO_2-absorber to form $(NH_4)_2SO_4$ (ammonium sulphate), which deactivates the ammonia for CO_2 capture. Also, the temperature of the flue gas will be lowered in the DCC to keep the water content low. The inlet flow of water to the CO_2 absorber needs to be the same as the outlet flow of water from the NH_3-absorber: Otherwise, the ammonia concentration in the system will be diluted (or concentrated).

2. **CO_2 capture section.** After the DCC the gases enters the CO_2 absorber in which the CO_2 is absorbed. The liquid from the CO_2 desorber is having an ammonia concentration of 6-10 Molal and a CO_2-loading of 25-35 % mols of CO_2 per mol of NH_3To keep the ammonia slip low, rich ammonia solution at a low temperature is introduced at the top of the CO_2 absorber. The rich solution is taken from the bottom of the CO_2 absorber. In the bottom of the CO_2-absorber the ammonia solution becomes loaded with CO_2 to 50-60 %.

This CO_2 rich stream is fed to the CO_2-desorber in which the CO_2 is stripped off. The CO_2-desorber is out of the scope of the CEMCAP project.

3. **CO_2-WW and CO_2 compression sections**. The CO_2 gas recovered in the CO_2-desorber is further purified in the CO_2-WW with a liquid water stream flowing in counter-current. The purified CO_2 gas stream is compressed to meet the specifications required for storage. Compression and storage is out of scope in the CEMCAP project.

4. **FG-WW section.** The outlet NH_3 gas concentration exiting the CO_2 absorber is 0.5-1.5 %vol. This is reduced to 100-400 ppm in the NH_3-absorber. In the bottom of the water wash the water contains a substantial amount of ammonia, which is sent to the NH_3-desorber for ammonia recovering and regeneration of the liquid water stream to be recycled to the top of the NH_3 absorber. The NH_3-desorber is not subject to investigation in CEMCAP.

5. **Recovery section**. To avoid water to accumulate within the system, a purge liquid stream is required. With the aim of avoiding losing ammonia and captured CO_2 within the purge stream, a recovery section composed of an appendix stripper is required. Almost pure water is obtained at the bottom of the appendix stripper, which is purged to close the water balance within the system. On the other hand, approximate 99 % of the ammonia and all CO_2 is recovered at the top of the column and sent back to the CO_2 absorber, minimizing the make-up of fresh ammonia solution.

6. **Flue gas heating section**. Finally, the CO_2 and NH_3-depleted flue gas leaving the NH_3 absorber passes through an acid wash column to almost completely remove the ammonia emissions and achieve the targeted flue gas temperature at the stack. This process is quite well understood and therefore not subject to investigation in CEMCAP.

3.2 GE’s experience from power applications

GE Power, at that time Alstom Power, identified 2006 CO_2 capture as a potential to curb CO_2 emissions from power production. GE Power, combined with former Alstom, has built approximately one-third of all fossil fuel capacity in the world and is still in a dominant position building new capacity. It was therefore important to be able to offer technic being able to capture CO_2. An extensive development program was initiated looking at different technologies those dedicated most effort was:

- Chilled Ammonia Process
- Advanced Amine Process
- Oxy-fuel

The rest of this chapter describes the efforts for the Chilled Ammonia Process.

3.2.1 SRI

SRI International (**SRI**) is an American nonprofit research institute headquartered in Menlo Park, California. The trustees of Stanford University established SRI in 1946 as a center of innovation to support economic development in the region.

In early 2006 SRI, with funding from Alstom Power, Inc. (Alstom), the Electric Power Research Institute (EPRI) and Statoil, conducted a proof-of-concept bench-scale testing of the novel CO_2 capture process - CAP (Chilled Ammonia Process) - based on the ammonium carbonate (AC)-ammonium bicarbonate (ABC) cycle. This test series demonstrated the ability to capture CO_2 from a simulated flue gas in ammoniated solutions. High CO_2 capture efficiency and high CO_2 loading including the formation of ammonium bicarbonate solids was demonstrated. Separately, regeneration of the CO_2 rich solution was demonstrated at a bench-scale level generating a high purity and high-pressure CO_2 stream.

Based on these results, Alstom, EPRI, and Statoil jointly co-funded a project commencing in May 2006 to design, construct, and operate a large bench scale pilot of an absorber system (mini-pilot plant). The overall objectives of operating the mini-pilot plant were:

i. Establish the potential to achieve 90% CO_2 removal efficiency with low ammonia emissions.
ii. Obtain CO_2 removal rates for various operating conditions to determine the liquid-to-gas (L/G) ratio and other design parameters for larger scale absorbers.
iii. Provide additional information for CO_2 absorber design; including a general understanding of the fundamental system parameters necessary to scale-up the process and construct a larger pilot plant.

All these objectives were achieved enabling Alstom to proceed with larger pilots.

3.2.2 Wisconsin Energy

Following the SRI tests, Alstom scaled up the CAP at a 1.7 MWe scale process development unit (PDU) located at We Energies Pleasant Prairie Power Plant (PPPP, “P4”), see Figure 2. The P4 tests demonstrated continuous operation on flue gas from a coal fired power plant and achieving up to 90 % CO_2 removal. The PDU commissioned between December 2007 and May 2008 with parametric testing operations continuing until the PDU was decommissioning in October 2009. In total, the PDU operated for approximately 7,000 hours.

Figure 2: WE Energy pilot plant.

The major achievements during the validation of the WE-CAP were:

- Capture efficiency of 88 % was achieved at design flow of 8000 Nm^3/h.
- Long term operation at steady state keeping ammonia concentration above 8 M.
- Confirmed high pressure CO_2 desorption operation.
- Confirmed low pressure NH_3 desorption operation.
- Successfully conducted absorber design tests.
- Low ammonia (2-3 ppm) in CO_2 product
    - High CO_2 concentration i.e. > 99.7 %.
    - Low ammonia emissions < 5 ppm.

3.2.3 AEP, West Virginia

A CO_2 capture and storage (CCS) pilot plant was constructed at American Electric Power's (AEP) 1300 MWe Mountaineer station in New Haven, West Virginia, employing Alstom Power's Chilled Ammonia Process (CAP). The CAP Product Validation Facility (PVF) was approximately a 12-fold scale-up from the 1.7-MW research and development pilot tested during 2008-9 at WE Energies' Pleasant Prairie Power Plant (P4) in Wisconsin. The AEP unit was designed to provide about 110,000 tons CO_2/year (100,000 metric tons CO_2/year) for injection into geological strata under the Mountaineer station. Approximately 1.5 % of the full load flue gas flow leaving the Mountaineer station wet scrubber (corresponding to approximately 20 MWe) was extracted and sent to the PVF for CO_2 capture and compression. The product CO_2 was then provided to an on-site injection, storage, and monitoring program. Treated flue gas, less the captured CO2, was returned to the Mountaineer station stack. The Mountaineer wet scrubber, stack, flue gas supply and return ductwork, and the PVF plant are shown in Figure 3.

Figure 3: Mountaineer Product Validation Facility plant.

The captured CO_2 was injected into two different geologic formations via two wells located within the plant boundary: Rose Run at ~7800 ft (2380 m) and Copper Ridge at ~8200 ft (2500 m). Three deep monitoring wells were drilled and equipped to monitor CO_2 containment, track carbon storage footprint, and measure downhole properties. The goal of the capture part of this project was for collaborative funders to be able to better judge the adequacy of the design and performance objectives for the chilled ammonia process through the information obtained on emissions (all media and pollutants), consumables, energy (how much energy, what form , and at what state conditions) and possibilities for thermal integration into a given power plant, the trade-offs between emission reductions and energy/reagent consumption, and plant operability and reliability.

The operations and testing phase began in third quarter 2009. Operations ended on May 28, 2011. During operation, AEP and Alstom successfully demonstrated that the Chilled Ammonia process system can produce high purity CO_2 suitable for injection in the geologic formations in the area of the plant, and that equipment configurations for commercial-scale CCS systems can be optimized. At reduced flue gas flow rates, the chilled ammonia process achieved the design objective of 75 % CO_2 removal efficiency and continuously met CO_2 product quality requirements.

The PVF operated for a total 7,901 hours while capturing 56,859 tons (51,173 tonnes) of CO_2 and storing 41,560 tons (37,404 tonnes) of CO_2.

3.2.4 Mongstad

Beginning in November 2011, the Chilled Ammonia Process at Test Centre Mongstad (TCM) operated for 6352 hours on CHP Flue Gas, RCC Flue Gas (refinery gas), and blended RCC Flue Gas, see Figure 4. During this operation, the ability of CAP to handle the full range of flue gas conditions and operating challenges was consistently demonstrated. These circumstances included:

- Variance in the CO_2 concentration of the flue gas from 3.6 vol% to 16 vol%
- Handle contaminants such as SO_X, NO_X, particulates, and oxygen without solvent degradation
- Refinery trips
- Loss of power
- Control system outages
- Flue Gas fan trips

The capability of the TCM CAP design to meet or exceed process objectives for CO_2 Capture Efficiency, CO_2 Product Quality, and Ammonia Emissions was consistently demonstrated throughout the operating period in which all of the events were experienced.

Summary of TCM tests:
Size: 80,000 MT/yr CO_2 capture
Plant: Natural Gas CHP, refinery (RCC)
Design CO_2 capture efficiency: 85%
NH_3 in residual flue gas < 10 ppm
CO2 product quality >99.5%
Operating hours: 6352 h

Figure 4: Mongstad test facility.

3.3 TRL in power application

During the years Alstom and later GE have conducted a range of pilot and demo testing as described in chapter 3. This experience has gained GE knowledge that from a TRL perspective would classify GE’s CAP into a level of 7 for power application.

This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.

3.4 Way forward in power application

Due to low activity in the market place no power application has been open for quote the last years. GE has however the capability to build a full-size EPC contract for a CAP unit and are prepared to do so based on our previous experience and present capabilities.

Our decision to follow such opportunity(ies) will remain a case by case decision, taking mainly into account to which extend the engineering efforts can be funded by developer or institutions and the probability whether the project will materialize,

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4 CAP PROCESS IN CEMENT APPLICATION FOR CO_2 CAPTURE

The CEMCAP project has defined a reference cement plant for which all partners in the project should base their assumption on. Chapter 4.1 briefly describes this plant, it should be noted that the entire description of the process has been taken from MS4.1 in the CEMCAP project, ref. [1]. Chapter 4.2 describes the main differences between flue gas from a typical cement plant and power plant. Chapter 4.3 summarizes the work done by GE and ETHZ in the CEMCAP project in deliverable D10.2 and chapter 4.4 work by ETHZ in deliverable D10.3. The deliverables are documented in ref. [2] and [3] respectively. All process simulation made by ETHZ in chapter 4.5 are based on the CEMCAP reference cement plant.

4.1 The CEMCAP reference cement plant (from MS4.1)

The reference cement plant is a Best Available Technique (BAT) plant defined by the European Cement Research Academy (ECRA). It is based on a dry kiln process, consists of a five-stage cyclone preheater, calciner with tertiary duct, rotary kiln and grate cooler. It has a capacity of 2,896 tonne clinker per day. This corresponds to ca. 1 Mt clinker per year, or 1.36 Mt cement per year, with a run time of >330 days per year. This is a representative size for European cement plants. The characteristics of the reference cement plant are summarized in Table 2.

Table 2: Characteristics of the reference cement plant.

Parameter	Value
Clinker production	2,896 t_{clk}/d
Clinker/cement factor	0.737
Raw meal/clinker factor	1.6
Specific CO_2 emissions	850 kg_{CO2}/t_{clk}
Specific electric power consumption	97.0 kWh/t_{cement} / 132 kWh/t_{clk}

The clinker burning line of the reference cement plant is shown in Figure 5. The raw material is first grinded in the raw mill, where it is also dried by hot flue gas from the preheater. The flue gas and the resulting raw meal are subsequently separated in a dust filter, and the raw meal is sent to the preheater while the gas is sent to the stack.

In the preheater the meal is heated by hot flue gas coming from the calciner and the rotary kiln. The meal and the hot gases are mixed for heat transfer and separated in cyclones arranged above one another. Thereafter, the raw meal enters the calciner, where the major part of the calcination ($CaCO_3 \Rightarrow CaO + CO_2$) is performed. Around 2/3 of the plant's total fuel input is consumed here to achieve the right temperature (~860 °C) and drive the endothermal reaction.

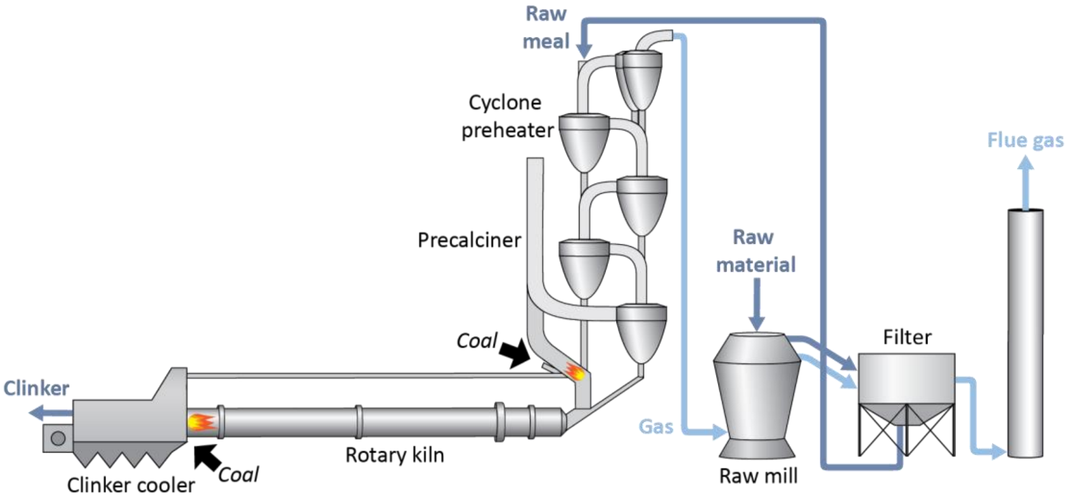

Figure 5: Clinker burning line in CEMCAP reference plant.

After the calciner, the raw meal enters the rotary kiln, where formation of the clinker takes place. Around 1/3 of the plant's fuel is burnt in the main burner, which is placed in the other end of the kiln. In the rotary kiln the solid material reaches 1450 °C, and the temperature of the gas phase can reach 2,000 °C. During its way through the rotary kiln the raw material components form clinker via intermediate phases. The hot clinker is discharged from the kiln to a clinker cooler. In the cooler ambient air is used to cool the clinker. Some of the resulting hot air is used as combustion air in the main burner (secondary air) and in the calciner (tertiary air).

A selective non-catalytic reduction (SNCR) system is installed in the kiln for control of NO_x emissions. SO_x emissions are below the limit of 400 mg/Nm3, set by the EU directive on industrial emissions, so no system is installed for SO_x emission control. The CEMCAP reference kiln is identical to the ECRA reference kiln, with the exception that a SNCR system is assumed to be installed in the CEMCAP kiln and not in the ECRA reference kiln.

The electric power consumption of the reference cement plant is associated with fans, coal milling and handling, raw meal and cement grinding, solids handling, etc. The power consumption distributed between the different users is presented in Table 3.

Table 3: Electric power consumption for the reference cement plant utilities.

	Flow rate [m^3/h]	**Flow rate [Nm^3/h]**	**Temperature [°C]**	**ΔP [kPa]**	**Power [kWh/t_{clk}]**
ID fan	349 440	162 564	314	6.35	6.40
Raw mill fan	411 712	293 512	110	10.70	12.70
Filter fan	584 117	439 355	90	1.80	3.03
Cooler fans	245 081	232 323	15	2.15	1.52
Coal milling and handling	-	-	-	-	5.81
Others (raw meal and cement grinding, solids handling, kiln drive, lightning, etc.)	-	-	-	-	102.14
Total	-	-	-	-	132

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4.2 Differences between power and cement process for CO_2 capture

In Table 4 have the difference in value for different components in a typical flue gas from a cement and power plant been summarized. The CO_2 concentration, which have a major influence on the CAP, is higher in the cement flue gas compared to power. Also, the SO_2 concentration in the flue gas is different, but not when a Flue Gas Desulphurization (FGD) unit is implemented in a power plant. The main difference, that needs to be addressed in the cement case compared to power, is the higher CO_2 concentration.

Table 4: Typical flue gas specifications from cement and power plant.

Component	Value cement	Value power
CO_2	14-35 vol%	10-12 vol %
O_2	5-14 %	4-8 %
H_2O	13-23 %	
SO_2	140-300 mg/m^3(stp)	1000-3000 mg/m^3
SO_2 with FGD	-	100-200 mg/m^3
HCl	4 mg/m^3(stp)	25 mg/m^3(stp)
NO_x (without SNCR)	800 mg/m^3(stp)	
NO_x (with SNCR, SCR in Power)	340 mg/m^3(stp)	
CO	1000 mg/m^3(stp)	1000 mg/m^3(stp)
Dust	5 mg/m^3(stp)	5 mg/m^3(stp)
Temperature	90-180 °C	60-180 °C

4.3 CEMCAP, experimental work (D10.2)

4.3.1 Main conclusions from experimental campaigns

- The CO_2 absorber test campaign has shown that coping with the increased CO_2 from the cement process will not cause any issues
- The DCC test campaign has shown that it is fully possible to reduce the SO_2 content in the gas to below 1 ppm using either NH_3 or NaOH as polishing media. This will reduce the deactivation rate of the media in the CO_2 absorber to almost nil.
- The water wash test campaign has shown that the higher CO_2 content in the gas will even improve the performance of the NH_3 polishing step.

4.3.2 Conducted experimental campaigns at GE Technical Center, Växjö

The objective of the first test campaign (out of three) was to investigate the influence of the higher CO_2 concentration in the CO_2-absorption column of the CAP. In the full scale industrial process, this column reduces the CO_2-content in the flue gas from about 20-30 vol% down to 2-3 vol%. A CO_2-absorption column in a full-scale plant is more than 25 m high, while the test facility is only 3 m high. For this reason, tests were planned with the aim of mimicking the flue gas conditions along the CO_2-absorption column expected in a full-scale CAP, i.e. the test matrix sliced the column so the CO_2 gas concentration varied between 5-30 vol%.

The goal of the second test campaign was to study the combined direct contact cooler (DCC) and SO_2-absorption. This unit reduces the SO_2 content below 1 ppm in the flue gas entering the CO2-absorber, avoiding the accumulation of SO_2 in the CO_2 absorption-desorption loop of the CAP.

The goal of the third and last test campaign comprised the study of the NH_3 -absorption column or the flue gas water wash section which reduces the NH_3 slip from 1 %, at the top of the CO_2-absorber, down to 200 ppm.

4.3.3 The Växjö CAP pilot at GE Technical Center

The Växjö CAP pilot is mainly designed for evaluating the capture efficiency in the CO_2 absorber, but it also includes a water wash, a regenerator (not used in this test campaign), a NH_3-stripper and an acid wash. A picture of the unit can be seen in figure 6.

Figure 6: Test rig at Växjö used for the pilot tests of the CO_2 absorber (CO_2 capture tests of the first experimental campaign) and the NH_3 absorber (NH_3 removal tests of the third experimental campaign).

The pilot is designed to be able to mimic any part of the absorption column in the chilled ammonia process. During the test campaigns, the absorption was evaluated in absorber 2, which has a packing height of 3 m and a diameter of 450 mm. The first absorber was used for generating a gas to the second absorber.

4.4 CEMCAP, CAP Process optimization (D10.3)

The CAP has been optimized for the application to cement plant flue gases using detailed equilibrium-based process simulations in the commercial simulator Aspen Plus. The simulations apply a state-of-the-art thermodynamic model for the CO_2–NH_3–H_2O system, which is based on an extended UNIQUAC framework and a set of model parameters that have been regressed using more than 3700 data from the literature, in the following called “Thomsen model”. Furthermore, a rate-based model has been developed based on literature data for the underlying system and has been used to generate a set of realistic Murphree efficiencies to be used in the equilibrium-based simulations.

The vast experience with the CAP application to coal-fired power plants supported the adaptation of the process to cement plant flue gases. The operating conditions have initially been adapted manually, starting from the typical operation of the CAP for coal-fired power plant flue gases (approx. 15 % CO_2) and applying basic design rules and intuitive understanding of the process. As a result, a set of operating conditions that allows robust CAP operation with cement plant flue gas while reaching competitive energy penalties could be identified. Starting from this reference and using the tools described above, a heuristic optimization of the CAP for cement plant flue gas has been carried out. The results of the optimization are presented in deliverable D10.3 of the CEMCAP project. In summary, it could be shown that the CAP can very well be adapted to cement plant flue gases without requiring changes to the basic process flowscheme. In addition, a very competitive energy demand compared to other CO_2 capture technologies could be confirmed, and the results are shown to be consistent with the CAP application to coal-fired power plants: indeed, it is possible to exploit the high CO_2 concentrations in the cement plant flue gas and achieve a lower energy demand per CO_2 avoided compared to the power plant application.

4.5 CAP process for cement application

4.5.1 PFD and heat and material balance

In Figure 7 is a principal flowsheet of the streams in a CAP connected to a cement plant

Table 5 reports the consumption numbers for a CAP unit connected to reference cement plant producing 3000 t/day of clinker according to Best available technology as defined in the European BREF document. The expected consumption numbers for the emissions of 100 ton of CO_2/h for a "standard cement plant" of 1,000,000 tons of clinker a year is 2.37 MJ of steam/kg CO_2 (58 MW).

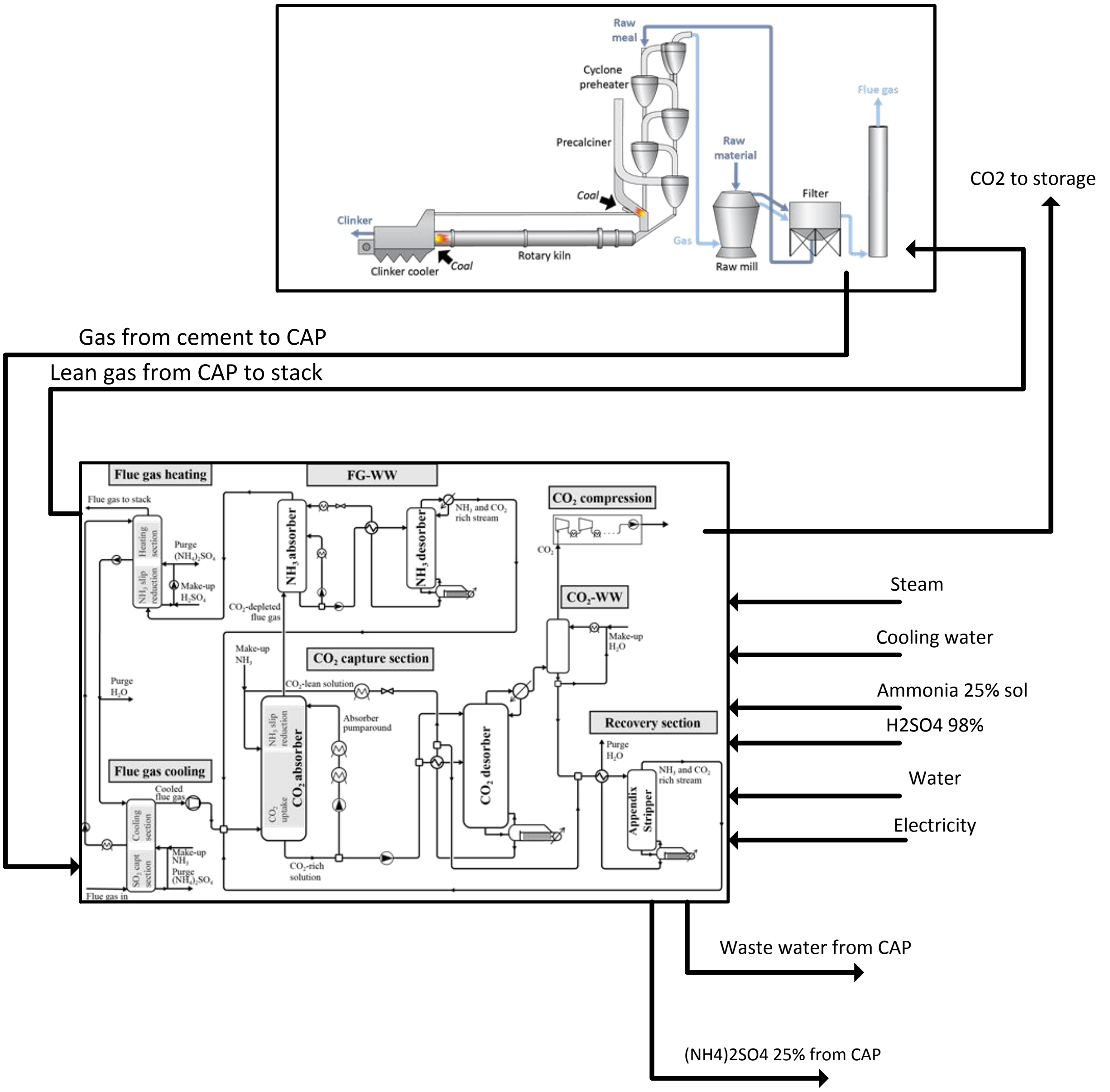

Figure 7: Principal flow-sheet for an integrated Cement-CAP unit

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Table 5: Consumption numbers for a CAP connected to reference cement plant of 3000 t/d clinker production. The numbers are taken from ETHZs work in D10.3, ref. [3].

Process gas from Cement plant		
Temperature	130	°C
Flue gas (mass flow)	316,800	kg/h
Flue gas (volumetric flow)	233,200	Nm^3/h
CO_2	22	% v/v
CO_2	101	ton/h
SO_2	70	ppm
SO_2	46	kg/h
Utilities to CAP		
Steam pressure	8	bar
Steam flow	95,000	kg/h
Steam power	54	MW
Cooling water flow	4,600	m^3/h
Cooling water power	54	MW
Water make-up	250	kg/h
NH_3 make-up	180	kg/h as 25%
H_2SO_4 make-up	40	kg/h as 98%
Process gas from CAP		
Temperature	47	°C
Flue gas (mass flow)	223,200	kg/h
Flue gas (volumetric flow)	182,300	Nm^3/h
CO_2	3.4	% v/v
CO_2	12.2	ton/h
SO_2	0	ppm
SO_2	0	kg/h
CO_2 to storage		
Flue gas (mass flow)	88.5	ton/h
Pressure	20	bar
Waste streams		
Water from DCC	4,000	kg/h
Water from CAP	250	kg/h
$(NH_4)_2SO_4$	580	kg/h as 25%

4.5.2 Integration opportunities and full site PFD

As in the case for a Power application where all required utilities already are available at site, a modified approach on how to integrate the units are relevant. This includes the building of a boiler in this case assumed being biomass fired. With such approach the cement plant could be CO_2 neutral or even having as this case negative CO_2-emissions of -160,000 tons/a.

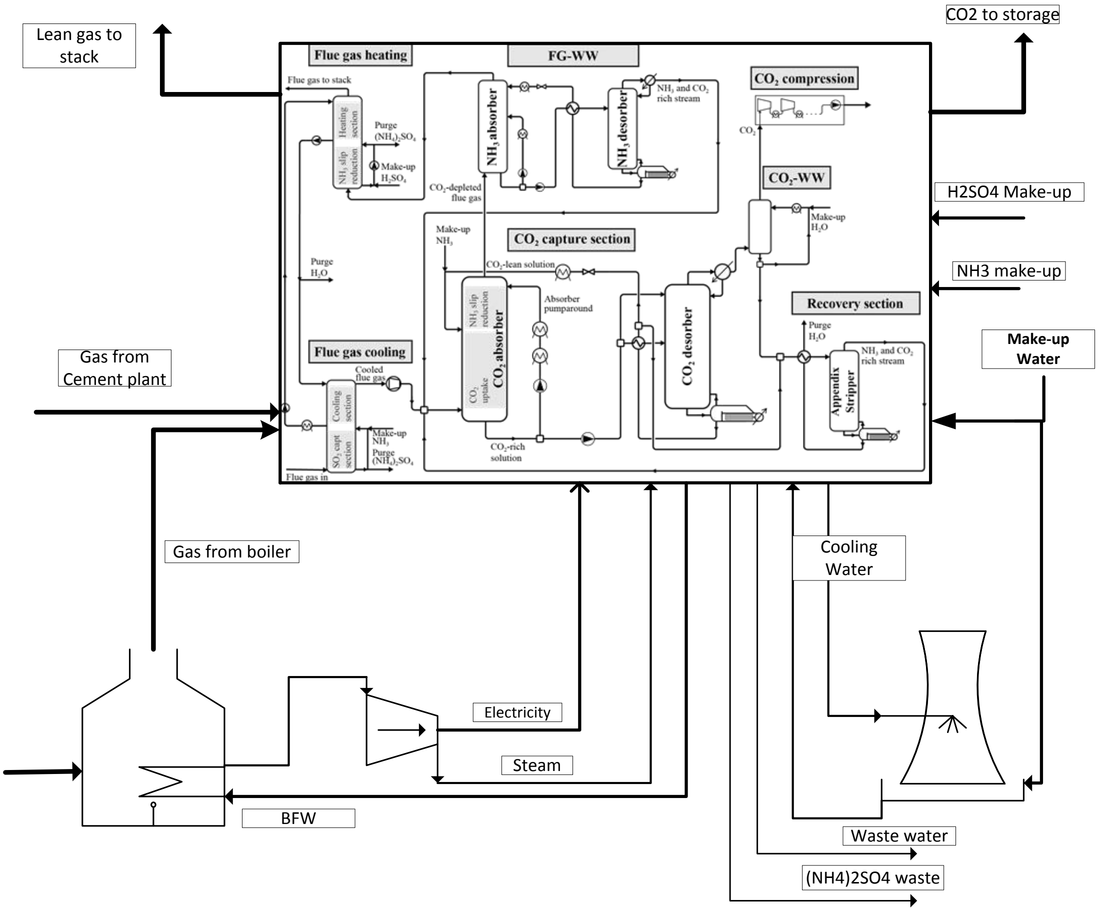

Figure 8: Flowsheet based on that the post combustion facility has all its utilities integrated.

Table 6: Consumption numbers for a CAP+Boiler connected to reference cement plant of 3000 t/d clinker production. The numbers are taken from ETHZs work in D10.3, ref. [3].

Process gas from Cement plant		
Temperature	130	°C
Flue gas (mass flow)	316 800	kg/h
Flue gas (volumetric flow)	233 000	Nm^3/h
CO_2	22	% v/v
CO_2	100	ton/h
SO_2	70	ppm
SO_2	46	Kg/h
NO_x	165	ppm
Process gas from boiler		
Temperature	130	°C
Flue gas (msas flow)	181,000	kg/h
Flue gas (volumetric flow)	141,000	Nm^3/h
CO_2	11.8	% v/v
CO_2	32.9	ton/h
H_2O	18.5	% v/v
O_2	4.9	% v/v
SO_2	70	ppm
SO_2	28	kg/h
NO_x	100	ppm
Utilities to CAP/Boiler		
Steam pressure	8	bar
Biomass flow (as dry)	17,600	kg/h
Biomass power	84	MW
Cooling water flow	7,200	m^3/h
Cooling water power	84	MW
Water make-up CAP	200	kg/h
Water make-up cooling tower	160	m^3/h
NH_3 make-up	240	kg/h as 25%
H_2SO_4 make-up	55	kg/h as 98%
Process gas from CAP		
Temperature	47	°C
Flue gas (mass flow)	375,000	kg/h
Flue gas (volumetric flow)	236,000	Nm^3/h
CO_2	2.8	% v/v
CO_2	13.0	ton/h
SO_2	0	ppm
SO_2	0	kg/h
CO_2 to storage		
Flue gas (mass flow)	120	ton/h
Pressure	20	bar
Waste streams		
Water from DCC	5 200	kg/h
Water from CAP	325	kg/h
$(NH_4)_2SO_4$	750	kg/h as 25%
Blowdown cooling tower	30	m^3/h

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If building the Chilled Ammonia unit combined with biomass combined heat and power unit would:

- Make the CCS+Boiler and the cement plant to a negative emitter of CO_2 with an emission unit of -160,000 ton/a (instead of 800,000 ton/a emitter)
- Make it a net producer of electricity.
- Consume about 675 GWh/a of biomass corresponding to 140,000 tons/a of CO_2.

5 STRATEGIC GUIDELINES FOR CAP DEVELOMENT INTO TRL 7 AND 8

5.1 Present TRL

For the CAP to be accepted on TRL of 7 the following must be fulfilled:

- System prototype demonstration in operational environment (with clinker quality maintained).
- For end-of-pipe technologies this means a full prototype operated with flue gas from operational cement kiln.
- For technologies that are highly integrated with the cement kiln, this means a prototype where all critical sub-systems are fully integrated.

GE has all these aspects fulfilled for the power application. However, the gases even if it on paper seems to be very similar, have not been operated in full scale for a cement application. The major difference between flue gas originating from a cement plant and a power plant is the CO_2 concentration, but minor contaminants may also differ. This difference in CO_2 concentration, and also SO_2 concentration, has been extensively tested in the CEMCAP project and has been proven not entailing any difficulties.

To be accepted for TRL of 6 the following must be fulfilled:

- Technology demonstrated in environment relevant to operation in cement kilns (conditions replicating industrial operation) with clinker quality maintained. Trace elements should be included in flue gas if relevant.
- Demonstration of the sub-systems affected by the cement conditions may be sufficient if the full system is demonstrated at TRL 6 or higher for other applications (e.g. power plants).

GE is fulfilling all these aspects for TRL of 6 for the cement application.

5.2 Required project work to achieve higher TRL

GE is fulfilling all the aspects in order to qualify for a TRL of 6 for the cement application. GE are also qualifying for a TRL of 7 in all aspects for the power application. These qualifications are based on the description in Chapter 3.2 “GE’s experience from power applications” in this report. The high level of readiness was achieved from the >7,000 hours in operation from the Mountaineer facility.

The greatest identified difference between the power and the cement application is the higher CO_2 content in the flue gas of the cement process. One of the most important work items for GE in the CEMCAP project has been to in detail study the impact of the increased CO_2 content described briefly in Chapter 4.2 in this report and more in detail in CEMCAP deliverable D10.2 *“Results from CAP pilot plant experimental campaign”*.

In order to reach TRL of 7 also for the cement application building a larger pilot or demonstration plant of at least 100,000 ton/a would be required. GE has the full EPC capability for executing such a project.

The same requirements for doing so applies for the cement application as the power application, i.e. to which extend the engineering efforts can be funded by developer or institutions and the probability whether the project will materialize,

6 CONCLUSION

GE has vast experience with the CAP for power plant applications, reaching TRL of 7 not only with a single plant but with a broad portfolio of pilot and demonstration plants in different environments, with different levels of integration into the full CCS chain (transport and storage of CO_2 have been included in the Mountaineer facility) and different fuels/flue gases.

The TRL of 7 has not formally been fulfilled for the cement application, however:

- The major difference between the flue gases of a cement plant and a coal-fired power plant is the higher CO_2 concentration, leading to some uncertainty on how the process needs to be adapted to best cope with the higher CO_2 concentration. Within CEMCAP, this major reason for uncertainty has been explored with very favorable results: The CAP can handle such high CO_2 concentrations with very minor adaptations, which can be limited to the operation, not involving changes in the basic process flowsheet of the process.
- Many other typical challenges for post-combustion CO_2 capture processes are less stringent in the cement application compared to the coal-fired power plant application. For example, the need for flexible operation of the plant due to frequent price fluctuations on the electricity market does not affect a cement plant and the levels of acidic impurities that typically disturb the CO_2 uptake by the solvent (SO_x and NO_x) are lower in a typical cement plant.
- As a post-combustion process, the CAP does by definition not affect the clinker quality, because it does not interfere with the cement process.

Hence, GE and ETH Zürich are with the work performed within CEMCAP project confident that there will be no major technical obstacles in demonstrating the CAP technology in an operational environment, i.e. to fulfill the formal requirements for TRL 7 in CEMCAP, and scaling up the process to reach higher TRL and market readiness.

7 NOTATIONS

AEP	American Electric Power
BAT	Best Available Technology
CaL	Calcium Looping
CAP	Chilled Ammonia Process
CCS	Carbon Capture Storage
DCC	Direct Contact Cooler
DFGD	Dry Flue Gas Desulfurization
DOE	Department of Energy
ECRA	European Cement Research Academy
EPC	Engineering Procurement Construction
EPRI	Electric Power Research Institute
ETHZ	Eidgenössische Technische Hochschule Zürich
GE	General Electric
ITO	Inquiry To Order
MEA	Mono Ethanol Amine
MS	Mile Stone
PFD	Process Flow Diagram
PVF	Product Validation Facility
RCC	Residual Catalytic Cracking
SNCR	Selective non Catalytic Reduction
SRI	Stanford Research Institute
TCM	Test Center Mongstad
TRL	Technology readiness Level
WP	Work Package
WW	Water Wash

8 REFERENCES

[1] Voldsund M, 2018, *“Cement plant performance with integrated CO2 capture and preliminary cost data (MS4.1)”*.

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[3] Pérez-Calvo J-F, 2018, *“Chilled Ammonia Process (CAP) optimization and comparison with pilot plant tests (D10.3)”*.