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Author(s)		
Name	**Organisation**	**E-mail**
Helmut Hoppe*	VDZ gGmbH	helmut.hoppe@vdz-online.de
Volker Hoenig	VDZ gGmbH	volker.hoenig@vdz-online.de
Johannes Ruppert	VDZ gGmbH	johannes.ruppert@vdz-online.de
David Berstad	SINTEF ER	David.Berstad@sintef.no
Matteo Romano	Politecnico di Milano	matteo.romano@polimi.it
Daniel Sutter	ETH Zurich	sutter@ipe.mavt.ethz.ch
Mari Voldsund	SINTEF ER	Mari.Voldsund@sintef.no

*Lead author

Keywords

CO_2, carbon capture, cement industry, oxyfuel, calcium looping, chilled ammonia, membrane-assisted liquefaction, MEA process, retrofitability

Abstract

This document provides a comparative study of the retrofitability of different CO_2 capture technologies which have been investigated within the framework of the CEMCAP project. Different criteria have been defined for a qualitative assessment of the retrofitability, e.g. the impact on the cement production process, the required equipment and associated footprint, additional utilities and services, the requirement of new chemicals or other substances and the existing operational experiences with the individual capture technology. The assessment of the retrofitability of the individual capture technologies was carried out with a color coding system. Only technical aspects have been taken into account, whereas economic assessments have been carried out in other work packages. The retrofitability of capture technologies is an important issue as the implementation of CCS in the cement sector will predominantly be carried out at existing kiln lines.

Changes in revision 1

Figures 4-6 and 4-7 are revised.

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1 INTRODUCTION

CEMCAP is a HORIZON 2020 funded research project about the capture of CO_2 emissions from cement kilns. The cement industry is one of the main industrial emitters of CO_2, which generates around 6 – 7 % of the total anthropogenic CO_2 emissions. Around 60 % of the emitted CO_2 is raw material generated due to the calcination of limestone. As for other industrial sectors, ambitious CO_2 reduction targets have been defined for the cement industry, which have to be met in the next decades [9].

In principal, three different approaches are possible to capture CO_2 from the flue gases of power plants and industrial combustion processes, namely pre-combustion, oxyfuel combustion and post-combustion processes [7], [8]. For cement plants and the clinker burning process, pre-combustion technologies are not appropriate as only the fuel-generated CO_2 could be reduced. Therefore, current research projects are focusing on post-combustion and oxyfuel technologies.

In the cement sector, only small-scale and pilot trials have been carried out so far. For the further development of the capture technologies, there is a need for large-scale or industrial-scale capture projects in the cement industry. It is likely, that new cement kilns could be equipped with different CO_2 capture technologies. However, as cement kilns have long operational lifespans of at least 30 – 50 years and the number of newly erected cement kilns per year is relatively small, the retrofit of capture technologies at existing kilns is an important issue.

The objective of this report was to elaborate criteria for an assessment of the retrofitability of the different CO_2 capture technologies which have been investigated within the CEMCAP project, namely the oxyfuel process, the chilled ammonia process (CAP), the membrane-assisted liquefaction (MAL) and the Calcium Looping (CaL) process. As a benchmark, also the MEA process (amine scrubbing with monoethanolamine) was included in the comparative study of different capture technologies, though no research has been carried out about this mature technology within the CEMCAP project.

The retrofit of the different capture technologies should be carried out at a so-called reference cement plant [2]. Different criteria have been defined and a qualitative assessment regarding the retrofitability has been carried out. It is clear that the preconditions for the installation of carbon capture technologies can be very different from plant to plant. This means, that a quantitative ranking of the different capture technologies would not make any sense. The study is focusing only on technical criteria and provides a qualitative assessment of criteria for retrofitting capture technologies at existing cement plants in Europe. An economic assessment of the different capture technologies has been carried out in other CEMCAP work packages [4].

A broader rollout of carbon capture technologies in the cement industry is not expected before 2025. This means that the first full-scale projects in the cement industry will still be R&D projects and more experiences about the retrofitability will be gained in the next years. However, several roadmaps about carbon capture in the cement industry have shown that the implementation of full-scale carbon capture plants in the cement industry has to be accelerated as soon as possible.

2 CCS VISION FOR THE CEMENT SECTOR

If the objectives of the different roadmaps for CO_2 capture in the cement industry shall be met, many existing cement kilns worldwide have to be retrofitted with carbon capture technologies. According to the International Energy Agency (IEA) there are ambitious CCS targets for the cement sector [1], [6]. **Table 2-1** shows the number of cement plants in 2030 and the percentage of all cement plants in the individual regions in 2050 which have to be equipped with carbon capture technologies.

Table 2-1 *CCS vision for the cement sector according to IEA; number of plants (2030) with carbon capture technologies or percentage of the plants (2050)[1]*

Continent / Region	**Year**	
	2030	**2050**
North America	30 plants	50 % *
Europe	30 plants	50 % *
India, China	15 plants	20 % *
Russia, rest of Asia	/	/
Japan, Australia, New Zealand	20 plants	50 % *
Africa	/	/
South America	/	/

* percentage of all cement plants in the individual region

It is expected that the limited number of new built cement plants could be equipped with tailor-made carbon capture technologies, taking into account all site-specific requirements. However, a limitation of capture only on new built cement kilns would by far not be sufficient to achieve the required CO_2 reduction rates, as cement kilns have a long lifetime of around 30 - 50 years. Therefore, it is most likely that existing cement kilns have to be retrofitted with CO_2 capture. For the selection of an appropriate capture technology the retrofitability is an important aspect, in addition to other criteria like energy use and cost.

The requirements for the installation of CO_2 capture technologies could be different from kiln to kiln. Therefore, the retrofitability of the different capture technologies is assessed for a reference cement plant (see **chapter 3**).

3 REFERENCE CEMENT PLANT

In the CEMCAP Framework Document [2] a so-called BAT [3] cement plant has been defined for different comparative assessments (see **Figure 3-1**). It comprises a dry process kiln with a five-stage cyclone preheater, precalciner with tertiary air duct and grate cooler which is equipped with the following emission abatement technologies: SNCR, dry additive process for SO_2 reduction, modern dust filter.

The reference cement plant has the following characteristics:

clinker capacity:	1 Mio. t/a (3,000 t/d)
cement production:	1.36 Mio. t/a
clinker / cement factor:	0.737
raw meal / clinker factor	1.6
specific CO_2 emissions:	850 kg CO_2/t clinker
specific total electrical energy demand:	97 kWh/t cement
emission level of relevant components:	10 mg/m^3 dust
	500 mg/m^3 NO_x (SNCR plant)
	200 mg/m^3 SO_2.

In a first approach the individual capture technologies have to be designed in an appropriate scale to achieve a maximum CO_2 reduction at the reference cement plant. However, it is likely that the first carbon capture projects could probably aim for partial CO_2 capture as first step towards the full-scale application of a capture technology.

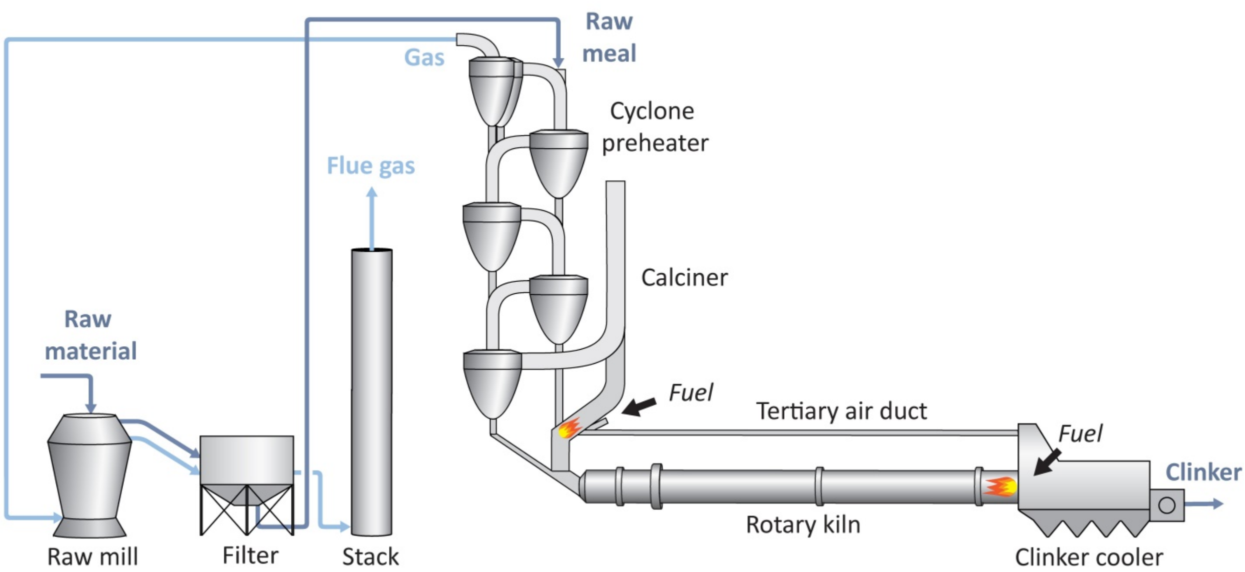

Figure 3-1 *Flow sheet of the kiln system in a reference cement plant*

4 CO_2 CAPTURE TECHNOLOGIES

Retrofitability has been evaluated for the following capture technologies:

- Chemical absorption with Monoethanolamine (MEA)
- Oxyfuel process
- Chilled Ammonia Process (CAP)
- Membrane-assisted Liquefaction (MAL)
- Calcium Looping (CaL), as
  - tail-end configuration, and as
  - integrated configuration

The oxyfuel process and the integrated configuration of the Calcium Looping process are technologies, which are highly integrated with the kiln system, whereas the others (MEA, CAP, MAL, CaL tail-end) are so-called post-combustion technologies, which are installed at the end of the flue gas route. This means that these technologies have no or only minor effects on the production process. Oxyfuel combustion and the integrated CaL process require significant modifications of the production process. Therefore, also the efforts regarding the retrofit of existing cement kilns with the different capture technologies are different.

To get an overall picture, the following subchapters contain short descriptions of the different CO_2 capture technologies.

4.1 MEA absorption

The MEA technology is a chemical absorption process for CO_2 capture which uses aqueous amine solutions as sorbents or "solvents". MEA is the most common amine, and many operational experiences are available from applications in different industrial sectors.

As a post-combustion process, the MEA plant would be installed after the dust filter before the stack (see **Figure 4-1**), without any modification of the cement kiln itself. In order to minimise the solvent degradation, effective emission abatement technologies for NO_x and SO_x have to be installed at the kiln. Steam is needed for solvent regeneration, so steam must either be generated at the plant or imported.

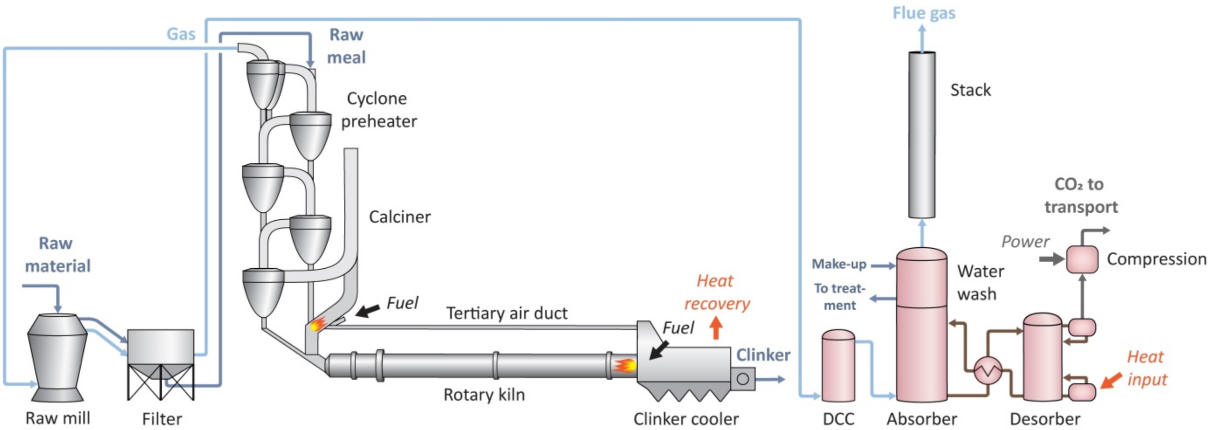

Figure 4-1 *MEA process for CO_2 capture at a cement kiln*

4.2 Oxyfuel process

The oxyfuel technology relies on the supply of pure oxygen and a gas mix of O_2 and recirculated CO_2 instead of ambient air for combustion. For this purpose nitrogen is removed by an air separation plant (ASU) from the air prior to being supplied to the kiln. Consequently the concentration of carbon dioxide in flue gas is increased significantly to about 80 vol.-%. At elevated concentrations of O_2 in the combustion gas the flame temperature in the sintering zone rises compared to ambient-air-based combustion. To maintain an appropriate flame temperature, part of the flue gas has to be recycled while the recirculation rate adjusts the combustion temperature. The flue gas leaving the oxyfuel cement kiln is purified and compressed in a CO_2 purification unit.

The principal configuration of an oxyfuel cement plant leaves the original reference cement plant in most parts unchanged. The modifications of the kiln system are illustrated in **Figure 4-2**. In terms of retrofitting an existing kiln plant the initial geometry of the equipment rotary kiln, preheater tower and calciner is kept unchanged. For the reason of gas tightness under oxyfuel operation the sealings have to be optimized compared to conventional operation. The process units that are operated in a CO_2 atmosphere and need to remain sealed include the clinker cooler, the rotary kiln, the calciner, and the pre-heater (see **Figure 4-2**). The raw mill is operated in an atmosphere of pre-heated air, where the heat is provided by the clinker cooler and by the raw gas via a heat exchanger..

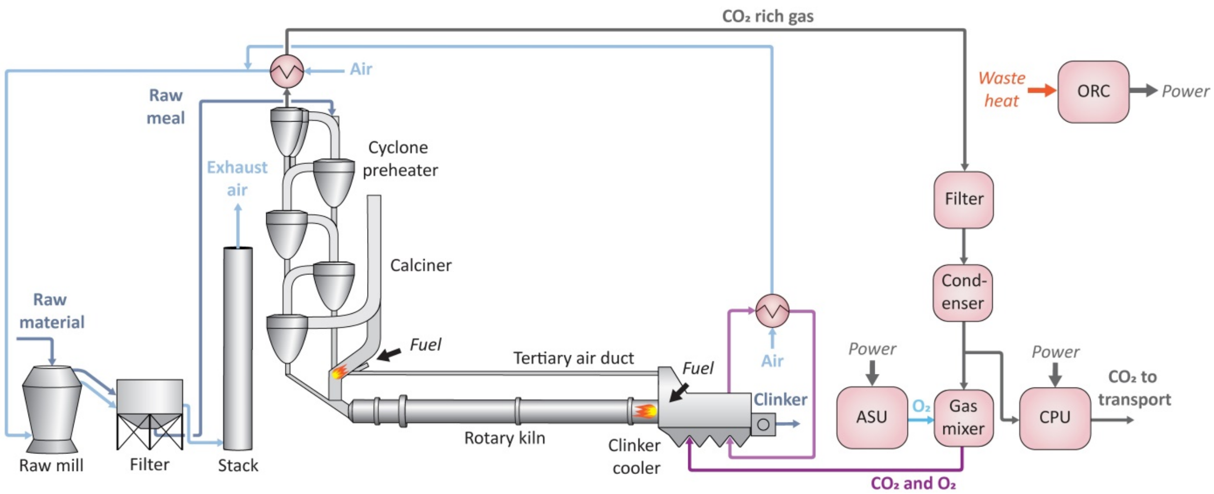

Figure 4-2: *Scheme of the oxyfuel cement plant*

4.3 Chilled Ammonia Process

The Chilled Ammonia Process (CAP) is similar to most of the amine-based scrubbing processes and is subdivided in three main sections, as can be seen from **Figure 4-3**: the flue gas cooling section, the CO_2 capture section, and the ammonia slip abatement section (generally called NH_3 water wash). The cooling of the flue gas in a direct contact cooler (DCC) and the ammonia-based desulfurization can be combined in the same unit, owing to the multi-pollutant control capabilities of the ammonia solvent. The cooled flue gases are then sent to the absorber, where the CO_2 concentration is reduced by the ammonia solution. The solution is regenerated in the CO_2 desorber by heating up the solution with steam at about 120 - 130 °C. High purity CO_2 leaves the column with a pressure up to 20 bar. The decarbonized flue gases are sent to the ammonia control section, where the NH_3 slip is reduced using cooled water before it is further conditioned by compression or liquefaction. The ammonia recovered from the treated flue gas and from the produced CO_2 is stripped in dedicated desorbers and is re-used in the CO_2 capture section. Similar to the amine-based capture processes, the CAP does not require any modification of the cement plant itself.

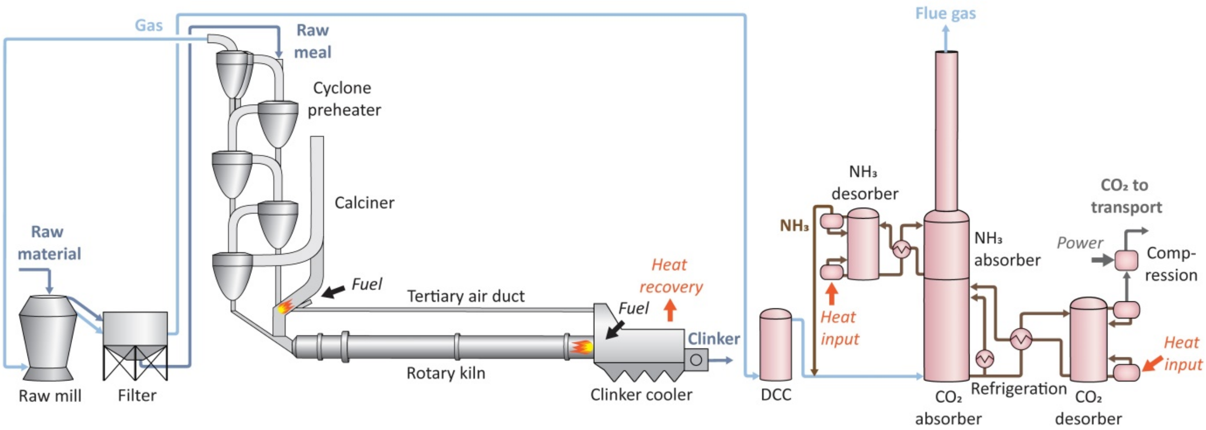

Figure 4-3: *Chilled Ammonia Process (CAP) layout*

4.4 Membrane-assisted liquefaction

The membrane-assisted CO_2 liquefaction (MAL) concept combines the polymeric membrane technology and a CO_2 liquefaction process. In a first step, polymeric membranes are used for bulk separation of CO_2 resulting in a moderate product purity. The driving force for the separation is the component partial pressure differential across the membrane. The purity and capture ratio attainable from a single stage membrane process depends on the membrane properties such as permeability and selectivity.

After that, the CO_2 rich gas stream is sent to a CO_2 liquefaction process where CO_2 is liquefied and the more volatile impurities (primarily nitrogen and oxygen) are removed. This two-step concept results in a high purity CO_2 gas stream. The MAL process is an end-of-pipe technology so that the actual clinker burning process is not affected. Only electrical energy is required as input for the process.

A simplified process scheme for the combination of membrane bulk separation and low-temperature CO_2 purification is shown in **Figure 4-4**.

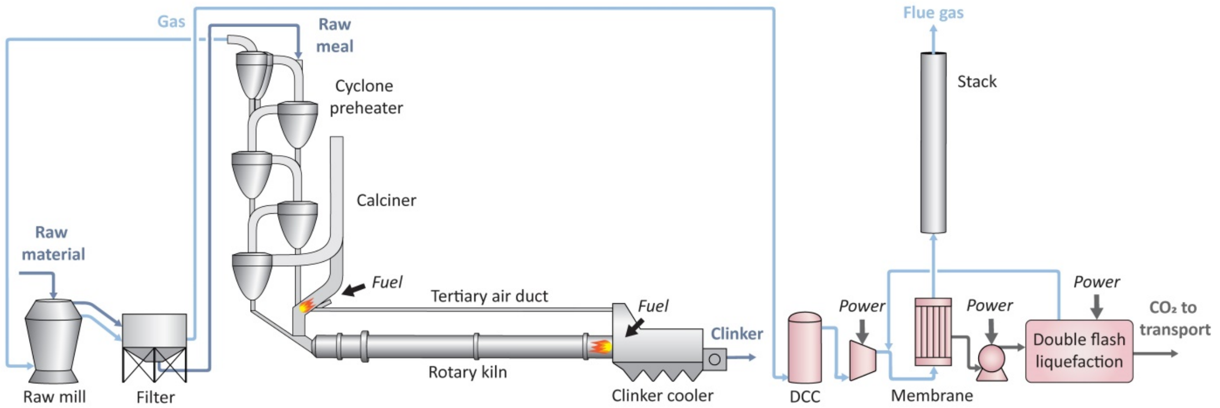

Figure 4-4 *Simplified process scheme for membrane-assisted CO_2 liquefaction*

4.5 Calcium Looping process

The Calcium Looping process (CaL) is a high temperature carbon capture process based on the cyclic calcination and carbonation of a calcium containing sorbent – generally limestone ($CaCO_3$). The process is based on the reversible reaction of calcium oxide (CaO) and carbon dioxide (CO_2) to calcium carbonate ($CaCO_3$).

$$CaO \quad + \quad CO_2 \quad \rightleftharpoons \quad CaCO_3$$

By means of cyclic carbonation and calcination (or regeneration) of the sorbent a CO_2 depleted gas stream and a CO_2 enriched gas stream is generated.

A general scheme of the Calcium Looping CO_2 capture process is shown in **Figure 4-5**. CO_2 is captured in the so-called carbonator by the forward exothermic reaction (carbonation reaction) depleting the entering flue gas from CO_2. By the means of a circulating solid the CO_2 is transported into a second reactor (calciner or regenerator) where the loaded sorbent is regenerated by the backward endothermic reaction (calcination reaction). Usually, the Calcium Looping process is operated in a dual fluidized bed system due to the good gas solid contact of fluidized bed reactors. However, entrained flow reactors may also be applied. In order to produce a highly concentrated CO_2 stream, the calciner is operated under oxyfuel conditions e.g. high CO_2 partial pressure.

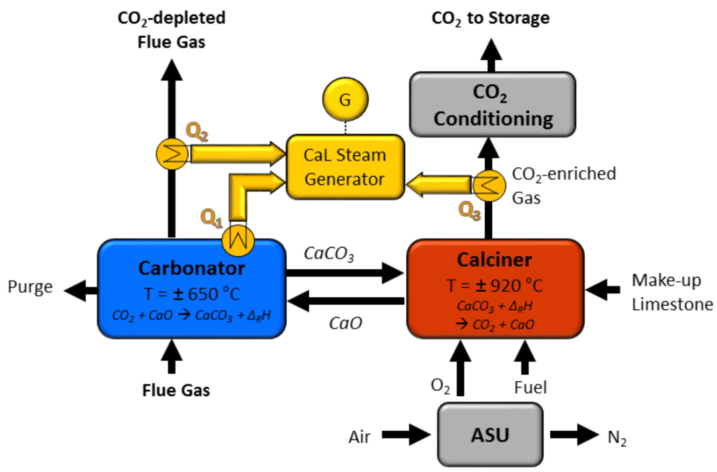

Figure 4-5 *General scheme of the Calcium Looping CO_2 capture process*

During the repetitive cycles, the sorbent's CO_2 carrying capacity decays. Therefore, spent sorbent must be purged from the system and replaced by fresh sorbent material (make-up) to maintain an active bed/sorbent.

Two different Calcium Looping CO_2 capture process schemes have been developed for cement kilns within the CEMCAP project. The first so called tail-end option is a standalone Calcium Looping CO_2 capture process that captures CO_2 from the flue gas exiting the cement plant's preheater tower (see **Figure 4-6**). This process is slightly integrated with the cement kiln, because the sorbent purge from the capture process is cooled, grinded, and mixed with the raw meal entering the cement kiln. The second so called integrated option treats the complete raw meal (see **Figure 4-7**). Therefore, two thirds of the cement plants CO_2 emissions are captured in the Calcium Looping calciner. The carbonator solely captures the CO_2 emission from the kiln. With increasing integration level the sorbent performance will improve and simultaneously the flue gas CO_2 concentration will be reduced since a larger share of the raw meal is already calcined by the Calcium Looping process. While the tail-end option is easy to retrofit, the energy efficiency is reduced compared to the integrated option that is more challenging to implement into an existing cement plant.

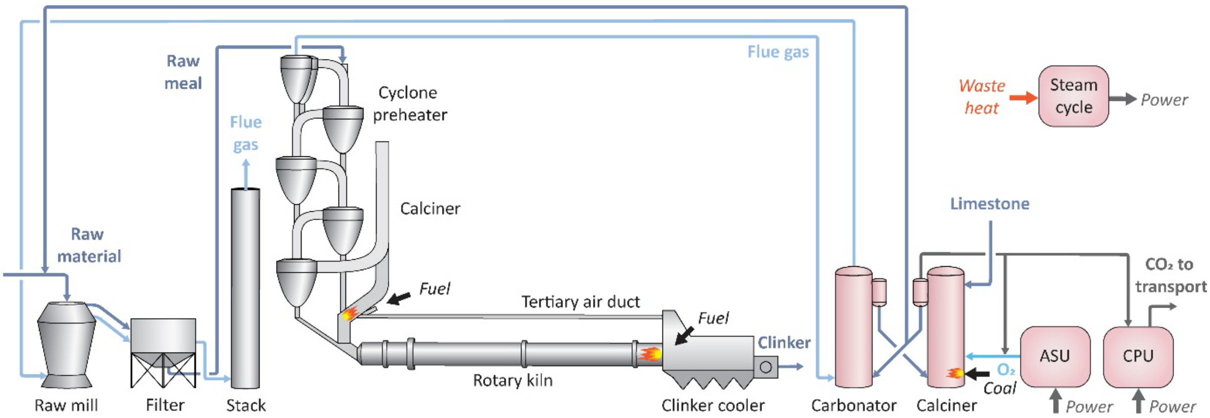

Figure 4-6 *CaL process – tail-end version*

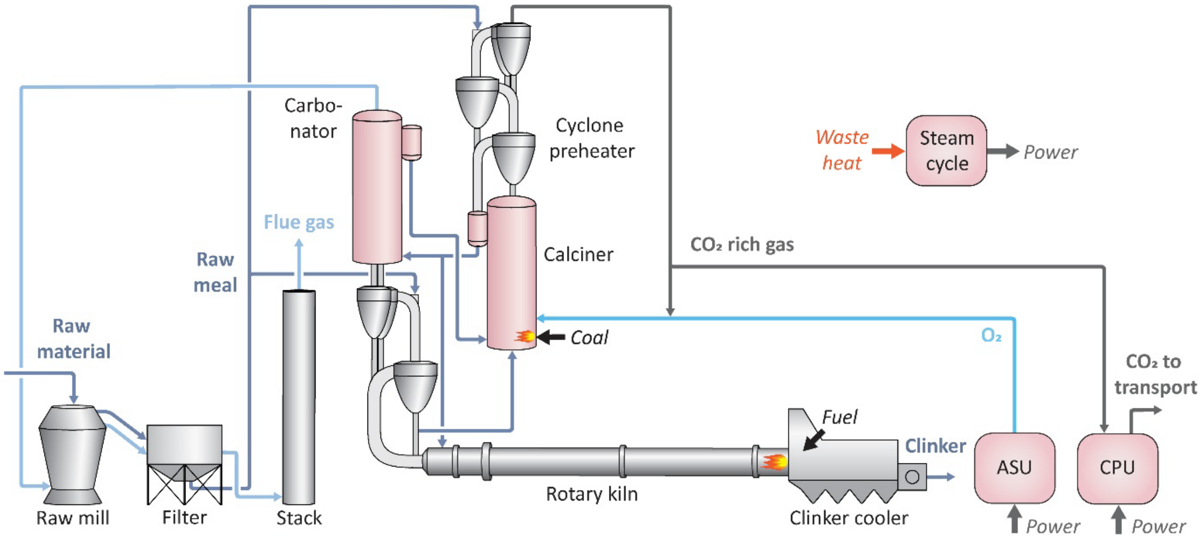

Figure 4-7 *CaL process – integrated version*

5 METHODOLOGICAL APPROACH TO ASSESS THE RETROFITABILITY

It is assumed that all carbon capture technologies, which have been investigated in the CEMCAP project, can in principal be installed at cement kilns. However, there might be requirements which could favour some technologies in comparison to others according to cement plant and site.

Against this background, the study has the objective to carry out a qualitative assessment of the retrofitability of the different capture technologies in a systematic manner and to find out which technologies are more or less suitable for a retrofit at a rotary cement kiln. Therefore, different criteria have been identified which could favour or impede the retrofit of the individual capture technology at a reference cement kiln. The different criteria are presented in the following **chapter 6**.

A colour coding system was used to assess the different capture technologies with respect to different retrofitability criteria. The following **Table 5-1** shows the selected colours, namely green for easy retrofit, yellow if some more attention is needed for a plant retrofit, orange for those cases where the retrofit would need special attention or important information is still missing, and red for cases where retrofit is considered impossible. In addition, symbols like checkmarks, exclamation marks, question marks and crosses are used to underline the effect of the different colours.

Table 5-1 *Traffic light system for the assessment of different retrofitability criteria*

colour / sign	meaning, explanation
✔	retrofitability o.k.; suitable in most cases/plants; in most cases no or significantly less attention needed
!	some attention needed for plant retrofit; assessment of plant specific conditions is important
!!	special attention needed for plant retrofit; key parameters have to be assessed in relation to site specific retrofitability
?	needs further assessment for plant retrofit; lack of important information
X	retrofit not possible

6 CRITERIA FOR THE ASSESSMENT OF RETROFITABILITY

The concept of the study is to carry out assessments for a list of specified criteria which could affect the selection of technology for retrofit of a cement kiln. The following criteria have been defined:

- impact on the cement production process
- equipment and footprint
- utilities and services
- introduction of new chemicals/subsystems
- available operational experiences

The assessment for the different criteria should be carried out only from a technical point of view – economic aspects have been investigated in other CEMCAP reports[4]. In the following subchapters the above mentioned criteria are explained and commented. The actual qualitative assessments are carried out in **chapter 7**.

6.1 Impact on the cement production process

This criterion includes aspects which could have an impact on the cement production. The most important aspect is the extent to which the operability of the plant could be affected. Secondly, it is assessed whether the quality of the produced cement/clinker could potentially be affected by the application of a certain carbon capture technology. Furthermore, if fundamental modifications of the cement kiln system are required, the extent of the construction work for installation of the capture technology has to be assessed, as long production stops could not be easy to accept in regions with high cement demand. These aspects have have been selected as first criterion, as the production of a high quality cement is the first priority of a cement plant operator – also in times of climate change with the urgent need to reduce the CO_2 emissions.

6.2 Equipment and footprint

The application of carbon capture technologies at cement kilns requires the installation of additional process-specific equipment (absorber, desorber, carbonator, etc.) and more general process units (ASU, CPU, refrigeration, boiler, etc.). This results in an additional space demand and the footprint of the required installations may be significant.

The footprint of a typical cement plant with a 3,000 t/d cement kiln is around 15 ha (150.000 m^2; cement plant including the quarries: 100 – 150 ha). It is assumed that if new equipment can be installed anywhere at the plant, the space demand can normally be handled, but retrofits would at least need some attention in every case. However, if the equipment must be installed near the kiln line, the footprint could be a limiting factor for individual capture technologies and more site-specific attention is required for assessing the applicability of these technologies as retrofit.

Furthermore, the principal availability of the required equipment and its robustness in long-term operation should be considered in this criterion.

6.3 Utilities and services

The application of certain carbon capture technologies requires additional utilities and services. This includes the need of additional electric power, steam (or NG for boilers), coal, or chemicals, dehumidification of flue gases or treatment of waste water. Out of this, the most limiting factor is the power demand, since the availability of electric power is dependent on the local grid capacity. Infrastructure for import of natural gas and coal normally already exists at cement plants, and an increase in the import of these fuels can be handled easily up to a certain point, before the capacity of infrastructure must be increased.

6.4 Introduction of new chemicals/subsystems

If new chemicals (e.g. MEA, ammonia, oxygen, etc.) or subsystems (ASU, refrigeration system, ORC, steam cycle, etc.) are introduced at the plant, new procedures and routines must be implemented to ensure safe operation. The utilization of new chemicals could also result in relatively complex permitting procedures. The permitting rules might vary from country to country. Therefore, the assessment will be carried out on a more general basis taking into account e.g. the environmental relevance of the individual chemical compounds.

When the captured CO_2 leaves the cement plant, it has to be stored or utilized. In many European countries there is no legal framework for the storage of CO_2. However, this important aspect is not included in this criterion, as this issue will be the same for all technologies.

6.5 Available experiences

For the installation of carbon capture technologies at cement kilns, technology maturity is important to limit the associated risks. The assessment should take into account the available experiences with the application at cement kilns, but also the available experiences from other industrial sectors like the power industry (coal fired power plants). In connection to this, also the scale-up of the technology is an important issue, as up to now no full-scale capture projects are in operation in the cement industry.

This aspect is particularly important for technologies that are integrated with the kiln line, since the reliability and availability of the capture technology then can deteriorate the availability of the whole kiln system. This aspect is addressed in the first criterion (see **chapter 6.1**)

7 ASSESSMENT OF THE INDIVIDUAL CAPTURE TECHNOLOGIES REGARDING THEIR RETROFITABILITY AT CEMENT KILNS

Following the methodology and the retrofitability criteria the individual capture technologies are assessed. A verbal assessment is carried out (see **chapter 7.1**) which is summarized in the subsequent tables. After that, a qualitative assessment of all capture technologies is carried out in a summary table with a traffic light system (see **chapter 7.2**). A ranking of the individual capture technologies was not intended as the preconditions for the application of the capture technologies can be very different from site to site and therefore the applicability of a certain capture process for retrofitting of an existing cement plant could be different from case to case.

7.1 Verbal assessment of the retrofitability criteria

7.1.1 MEA process

The MEA process was included in the retrofitability study as it is the most mature carbon capture technology and a lot of information is available about this process. The results of the assessments are summarized in the following **Table 7-1**.

Table 7-1 *Retrofitability assessment of the MEA process*

Criteria	Information / data description / etc.
Impact on cement production	▪ post-combustion process ▪ no fundamental modifications of clinker burning process (possibly heat recovery) ▪ short production stop for the rerouting of the flue gas ▪ clinker quality is not affected
Equipment and footprint	▪ most equipment can be installed away from the kiln line
Utilities and services	▪ significant additional power demand ▪ large steam demand ▪ MEA solvent required
Introduction of new chemicals/subsystems	▪ amines
Available experiences	▪ mature technology ▪ operational experiences from other sectors available ▪ scale-up not a critical issue

The MEA process is a post-combustion process which is installed after the dust filter and before the stack. Therefore, the clinker burning process is not affected by the application of this technology. During the construction phase the kiln has to be stopped only for a short period for the rerouting of the flue gas.

Additional installations like absorber and desorber columns are required for the MEA process and furthermore also general units like pumps, heat exchangers, fans. Furthermore, a large amount of steam is required. This could be generated in a natural gas (NG) fired boiler at the plant, resulting in an increased demand for NG and additional space at the plant. Alternatively and if really available it could be imported from a nearby power plant. Some additional power demand (around 14 MW) is also associated with the process.

The MEA technology introduces amines at the plant, which is a new chemical in a typical cement plant. The permitting process could be more complex than for other capture technologies, and new procedures and routines are required.

In general it can be said that the retrofit of the MEA process at a cement kiln would be associated with relatively low risks as many operational experiences are available from other industrial sectors. Also the scale-up of the required installations seems to be a manageable issue.

7.1.2 Oxyfuel combustion

The oxyfuel combustion is a process-integrated carbon capture technology which is based on the combustion with a mixture of oxygen and recycled CO_2-rich flue gas. This results in a substantial modification of the production process, but according to the current state of knowledge all challenges seem to be solvable. The result of the assessments is summarized in the following **Table 7-2**.

Table 7-2 *Retrofitability assessment of the oxyfuel combustion*

Criteria	Information / data description / etc.
Impact on cement production	▪ clinker burning process needs significant modification ▪ up to 6 months stop of clinker production due to the construction work ▪ conditions for the clinker production are changed, but seem to be manageable
Equipment and footprint	▪ new equipment has to be installed in the vicinity of the kiln ▪ substantial space demand
Utilities and services	▪ significant additional power demand
Introduction of new chemicals/subsystems	▪ ASU ▪ possibly ORC and thermal oil
Available experiences	▪ limited applicability of operational experience available from the power sector

The oxyfuel process requires a lot of additional equipment, e.g. process-specific units like an oxyfuel clinker cooler, an exhaust gas recirculation system, a gas-gas heat exchanger, a condensing unit and general units like an air separation unit (ASU), a CO_2 purification unit (CPU), a rotary kiln burner for oxyfuel combustion, an Organic Rankine Cycle (ORC), etc.

The application of the oxyfuel process and the on-site production of oxygen have a significant additional power demand (around 20 MW) which could be a critical issue in certain regions. Also, an ASU and possibly an ORC and thermal oil are introduced at the plant, which would require new procedures, routines, and permits, though O_2 production is a state-of-the-art process in many countries and different sectors.

Up to now there are only limited operational experiences with the oxyfuel process, e.g. from the power sector. However, much research work has been carried out in the last years within the

ECRA CCS project and also in the CEMCAP project. ECRA is now ready to carry out large-scale demonstration projects so that many operational experiences could be gained in the next years.

7.1.3 Chilled Ammonia Process

The Chilled Ammonia Process (CAP) is a post-combustion process and follows the same technology principle as the MEA absorption. The actual clinker production is not affected. During the construction phase the clinker production has to be stopped on for a short period during the rerouting of the flue gas. The results of the assessments are summarized in the following **Table 7-3**.

Table 7-3 *Retrofitability criteria of the Chilled Ammonia Process*

Criteria	Information / data description / etc.
Impact on cement production	▪ post-combustion process ▪ no fundamental modifications of clinker burning process (possibly heat recovery) ▪ short production stop for the rerouting of the flue gas ▪ clinker quality is not affected
Equipment and footprint	▪ most equipment can be installed away from the kiln line
Utilities and services	▪ additional power demand ▪ medium steam demand ▪ ammonia solution required as solvent
Introduction of new chemicals/subsystems	▪ ammonia ▪ refrigeration system
Available experiences	▪ certain operational experiences available from NG and coal-fired power plants

The CAP would be installed after the filter before the stack, i.e. no modifications of the cement kiln itself are needed. For the application of this technology process-specific units like several packed absorption and desorption columns and direct contact coolers. Furthermore, general units like coolers, pumps, heat exchangers, etc. are also needed. As the CAP is a tail-end process, most of the required equipment could be installed away from the kiln line, so that the space demand is moderate. There is no need for additional NO_x and SO_x abatement units, since NO_x is reduced by the ammonia solvent or passes through the CAP and SO_x is removed in the CAP direct contact cooler.

Steam is required for solvent regeneration, and some additional power (around 8 MW) is required for refrigeration, compression and pumping etc. Both the steam and power demands are lower than for the MEA process.

A refrigeration system is necessary, so refrigerants (possibly ammonia) are introduced at the plant. The solvent, an aqueous ammonia solution is also introduced at the plant. Aqueous ammonia is a chemical that the cement industry has experience with, from SNCR and SCR systems. However, the permitting process could be a little bit more complex due to the environmental relevance of ammonia.

CAP is a promising technology for post-combustion CO_2 capture and certain operational experiences are already available from the power sector. Due to the chemical stability of the solvent and the available experience, the installation of the CAP at cement kilns seems to be associated with only moderate risks.

7.1.4 Membrane-assisted liquefaction

The membrane-assisted liquefaction (MAL) is a post-combustion process, so the actual clinker production is not affected. The installation at a cement kiln line would require only a short stop of the clinker production during the rerouting of the flue gas. The result of the assessment is summarized in the following **Table 7-4**.

Table 7-4 *Retrofitability assessment of the MAL process*

Criteria	Information / data description / etc.
Impact on cement production	▪ post-combustion process ▪ no impact on clinker burning process required ▪ short production stop for rerouting of the flue gas ▪ clinker quality is not affected
Equipment and footprint	▪ footprint similar to MEA process ▪ most equipment can be installed away from the kiln line
Utilities and services	▪ significant additional power demand ▪ no steam required
Introduction of new chemicals/subsystems	▪ refrigeration system
Available experiences	▪ maturity of membrane is critical ▪ depends on membrane type – fixed site carrier (FSC) membranes tested at Norcem plant

The MAL process needs additional process-specific units like the membrane modules and general units like the refrigeration system, coolers, fans, pumps and heat exchangers, compressors and separators are required for the application of this technology. Most of the required equipment could be installed away from the kiln line, so the space demand seems to be manageable (footprint similar to MEA process).

The only additional utility required is electric power. The power demand is significant (around 34 MW), so the capacity of the local electric grid could be an issue.

No new chemicals are introduced at the plant, except for refrigerants (propane, ethane, ammonia, etc.) associated with the refrigeration system.

The MAL process is a combination of two technologies; membrane technology and liquefaction technology. The membrane technology is the limiting factor when it comes to the maturity of the process. The membrane tested in CEMCAP has a low maturity for the cement application, whereas other membranes have been tested in operational conditions.

7.1.5 Calcium Looping – tail-end configuration

The tail-end Calcium Looping system would be installed either before the raw mill or after the dust filter. Installation before the mill gives advantages in terms of higher CO_2 concentration in the flue gas, and handling of smaller gas volumes, while there normally is more space available after the filter. The CaL tail-end process is slightly integrated with the cement kiln since sorbent purge is grinded and used as raw meal in the kiln. However, this does not include any risk for the plant operability or the clinker quality. Like for other post-combustion technologies the installation of the CaL process (tail-end version) would require only a short production stop during the rerouting of the flue gas. Additional utilities like coal and limestone are needed, which is daily business in cement plants. However, only certain limestone qualities are suitable for the CaL process, and this varies significantly from plant to plant. The actual production process and the clinker quality are not affected. The results of the assessments are summarized in the following **Table 7-5**.

Table 7-5 *Retrofitability assessment of the Calcium Looping (CaL) process – tail-end version*

Criteria	Information / description / etc.
Impact on cement production	▪ post-combustion process ▪ no fundamental modifications of clinker burning process ▪ sorbent purge is used as raw material (no risk) ▪ short production stop for rerouting of the flue gas ▪ clinker quality is not affected
Equipment and footprint	▪ most equipment can be installed away from the kiln line
Utilities and services	▪ additional coal demand; ▪ integrated power generation (low power demand or some power export depending on integration level) ▪ infrastructure for power export might be needed ▪ chemicals for production of demineralized water required (steam cycle) ▪ a certain limestone quality needed
Introduction of new chemicals/subsystems	▪ ASU ▪ steam cycle
Available experiences	▪ limited operational experiences available, e.g. from small-scale-demo plants

The application of the CaL process requires additional process-specific units like oxyfuel calciner and the carbonator and also general units like an ASU for the oxygen production, a CPU, a refrigeration system, a steam cycle for power production and installations for fuel and sorbent preparation. However, no additional flue gas treatment is required. The footprint of the additional equipment including the associated auxiliaries and the possible power production needs a site-specific assessment, but it could be installed far away from the kiln line.

There is no requirement for steam in the process, but steam will be generated from waste heat for a steam turbine system, so a boiler and steam turbine must be installed. An ASU and a CPU is also required in the process. The sorbent in the calcium looping technology is CaO, which is already well known at cement plants. A new chemical introduced at the plant is oxygen, which would require permits and new procedures and routines.

Up to now, there are only limited operational experiences available, e.g. from a small-scale-demo plants in the power sector.

7.1.6 Calcium Looping – integrated configuration

In the integrated version of the CaL process the calciner and the preheater of the cement kiln are modified and the CO_2 capture is part of the clinker burning process. Therefore, this capture process affects the clinker production process and probably also the clinker quality. However, it is assumed that fuel ashes and sulfur compounds can be incorporated in the clinker, so that this challenge is manageable. The result of the assessments is summarized in the following **Table 7-6**.

Table 7-6 *Retrofitability assessment of the Calcium Looping (CaL) process – integrated version*

Criteria	Information / description / etc.
Impact on cement production	▪ preheater and calciner modification required ▪ potential impact on the clinker production ▪ long production stop during the construction work
Equipment and footprint	▪ moderate to high footprint close to the kiln line and the preheater
Utilities and services	▪ additional coal demand ▪ low additional power demand ▪ a certain limestone quality needed
Introduction of new chemicals/subsystems	▪ ASU ▪ steam cycle
Available experiences	▪ very early stage of development ▪ scale-up of the reactors could be a critical issue

For the operation of an integrated CaL process, process-specific units like entrained flow reactors for the calciner and the carbonator are needed and furthermore general units like fans, cyclones, an ASU for oxygen production, a CPU, a steam cycle for power production and installations for the fuel preparation are needed. However, no additional flue gas treatment is needed. The footprint of all additional installations is moderate to high, and a certain space demand is given close to the kiln line and the preheater tower which could be a limiting factor for a retrofit.

Like for the tail-end version, oxygen is needed for the oxyfuel fired calciner. Also in this case the availability of high-temperature waste heat would allow the production of electrical energy.

The integrated CaL process is in a very early stage of development so that a retrofit of this technology would be associated with significant risks. Operational problems with the carbon capture process could lead to a reduced availability of the kiln line which is a critical issue for cement plant operators.

7.2 Comparative assessment of the retrofitability of all capture technologies

The comparative assessment of all included capture technologies is based on the methodology for qualitative assessment (see **chapter 5**), the retrofitability criteria (see **chapter 6**) and the verbal assessment of the individual capture technologies (see **chapter 7.1**). The results are shown in **Table 7-7**.

***Table** 7-7 Comparative assessment of the different capture technologies regarding their retrofitability at cement kilns*

	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	✔	?	!	?	!	?

Criterion no. 1 is about the impact on the cement or clinker production and includes the process technology, the potential for affecting the clinker quality, and also required production stops during the construction phase. The application of post-combustion technologies does not affect the actual clinker burning process or the clinker quality, as the required additional equipment is installed at the end of the process. During the construction phase, only a short stop of the clinker production would be required for the rerouting of the flue gas. The CaL tail-end process is slightly integrated with the cement kiln since sorbent purge is grinded and used as raw meal in the kiln. However, this does not include any risk for the plant operability or the clinker quality. Therefore, all post-combustion technologies are marked green. The process-integrated technologies, namely the oxyfuel process und the integrated CaL process, require a more significant modification of the production process. As a result of it, potential operational problems due to the capture technology will directly affect the operability of the plant. Furthermore, a long production stop is required during the construction phase. The changes in the production process could probably affect the clinker quality. However, according to the current state of knowledge, changes of the gas atmosphere, of gas temperatures and other process conditions can be managed, so that an optimum clinker production can be achieved. Nevertheless, due to the remaining uncertainties these technologies are marked yellow and orange. It should be mentioned that for the oxyfuel process, both the clinker cooler, rotary kiln, calciner, and preheater are amended, whereas for the integrated

CaL technology only the calciner and preheating tower are changed, while the cooler and the kiln are not modified.

With criterion no. 2 the required space demand for additional equipment is assessed. It is clear that every capture process will need additional installations which require available space. The most important difference between the technologies is made by whether the equipment has to be installed close to the kiln line or if it can be installed further away. In many cement plants, there is only limited free space around the kiln so that the process-integrated technologies like the oxyfuel combustion and the integrated CaL process require special attention to site-specific circumstances for retrofitting compared to the post-combustion technologies. Lack of the necessary space is an issue that could limit the implementation of these processes at certain kilns. Therefore, the oxyfuel and the integrated CaL processes are marked orange. In contrast to this, there is more flexibility with the retrofit of post-combustion technologies as free space is only required somewhere in the cement plant.

The new installations could be erected there and only the total amount of required space and the length of the gas ducts from the kiln line to the capture unit and back from there to the stack has to be considered.

However, a significant space demand is given and a site-specific assessment would be required in every case, so that the post-combustion technologies are marked yellow in case of this criterion.

Criterion no. 3 is about the required utilities and services and includes power demand, steam demand, coal demand, the need of certain chemicals, infrastructure for power export, etc.

The MEA process needs monoethanolamine which should become available everywhere and thus should not be a counterargument against a retrofit of this technology. The high steam demand is of higher relevance. The steam could be generated in natural gas (NG) fired boilers, which would require substantial import of NG, or supplied by a power plant in the vicinity of the cement plant. Furthermore, significant additional power is required. With the high steam demand, and the extra power demand, site-specific conditions such as the capacity of the NG grid and the power grid must be assessed and could limit the retrofitability. Therefore the MEA process is marked in yellow.

Regarding the required utilities and services the CAP is assessed similarly as the MEA process. In this case also steam is required for the solvent regeneration, and some additional power is required for chilling, compression, etc. Ammonia solution is used for the CO_2 capture and an acid for the flue gas treatment or NH_3 abatement respectively. Both chemicals should be available and should not impair the retrofitability of the CAP. As a result of this the CAP is marked yellow.

For the oxyfuel process, additional electric power for the CPU, ASU, etc, is needed. Although this is the only extra utility that is needed, the amount of power that is needed is also significant. This could be problematic in some regions if the capacity of the electrical grid would be limited. For this aspect, the retrofit of the oxyfuel process would need an assessment of the site-specific conditions and is therefore also marked in yellow.

The MAL process is similar to the oxyfuel process in the sense that the only extra utility needed is a significantly higher electric power demand. Since the amount of power required is large, site specific considerations must be taken with respect to electric grid capacity, so the technology is marked yellow.

For the CaL processes, electrical power is also needed for the ASU, CPU, etc. On the other hand electric power can be produced at the plant due to the availability of high-temperature waste heat. Depending on factors such as integration level, the net power consumption at the plant can be positive or negative. If there is power export from the plant, infrastructure would be required for this. If the power generation is balanced with the power consumption, there would not be any need for import of power, which is an advantage. Other utilities needed are additional coal (for oxyfuel combustion in the calciner) and limestone (sorbent in the capture process). These are generally well-known in cement plants and available everywhere. However, only certain limestone qualities are suitable for the CaL process, and this varies significantly from plant to plant. Some attention is needed for the plant retrofit, with respect to import/export of power, additional coal demand, and limestone quality. The two CaL processes are therefore marked yellow.

Criterion no. 4 evaluates to which extent processes with new subsystems or new chemicals must be introduced at the plant for the different capture processes. The operation of the MAL only requires the installation of a refrigeration system, which implies that refrigerants will be present at the plant. This should be relatively easy to handle, and therefore this technology is marked in green. All capture technologies, which require the production and the use of oxygen, could require a more complex permitting process and site-specific conditions could play a role. Therefore, the oxyfuel and the CaL process are marked in yellow. The MEA process and the CAP need amines or ammonia as solvent which have a high environmental relevance. Despite the fact that significant experience in their handling and permitting exists from other industries, the permitting process could be more extensive compared to the other technologies. Nevertheless, an overall assessment leads to a mark in yellow, indicating some attention is needed for the site-specific handling of new chemicals.

With criterion no. 5 the available operational experiences are assessed. The MEA process is the most mature capture technology and a lot of information is already available. Other types of amines have been tested for flue gas from an operational plant, and it can be expected that a retrofit should be possible without major problems. Furthermore, it is likely that the availability of the kiln system should not be reduced significantly. Consequently, this technology is marked in green. In contrast to this, the integrated CaL process is in a very early stage of development and the TRL is still low. Therefore, retrofits of this technology at cement kilns would be associated with significant uncertainties so it is marked orange. For the oxyfuel process, the CAP and the tail-end CaL, operational experiences are available at least from the power sector and mostly from small-scale projects. However, due to the fact that the CAP and the tail-end CaL are post-combustion technologies and do not affect the cement production process, the experience from the power sector can be much more directly applied to the cement environment. As a result of it, these technologies are marked in yellow, while the oxyfuel technology is ranked orange, but with less uncertainty than MAL and integrated CaL. For the MAL process the overall maturity is dependent on the maturity of the membrane. The membrane tested in CEMCAP has a low maturity for the cement application, whereas other membranes have been tested in operational conditions. This technology is marked orange by assuming the application of the CEMCAP membrane, although it would be yellow with a more mature membrane type.

8 SUMMARY AND CONCLUSIONS

The retrofitability is an important aspect for the future roll-out of carbon capture technologies as cement plants have a long lifetime between 30 and 50 years. It is likely that in most cases a capture technology will be installed at an existing kiln and not at a new green-field plant. In this case the retrofitability of different capture technologies will be compared against one another. Therefore the present study has been elaborated to identify the pros and cons of different carbon capture technologies regarding their retrofitability. It was intended to make a qualitative assessment and not a ranking list of the different technologies. The study has focused only on technical aspects – economic assessments have been carried out within the framework of other studies in the CEMCAP project [4].

The MEA process was included in the study as many operational experiences are already available. The conducted assessment shows a relatively good retrofitability, but associated with uncertainties regarding the extent of the permitting process and the high energy and steam demand.

The assessment shows that retrofit of the oxyfuel process requires more attention to site-specific technical solutions. It is evaluated as yellow or orange for all criteria. This does not yet represent the current situation. Extensive research has been carried out in the last years (e.g. within the ECRA and the CEMCAP projects) and potential challenges and problems have been identified which could discriminate the applicability and the retrofitability of the oxyfuel process at cement kilns. Based on these research results, it is expected that most challenges can be met and that the oxyfuel process can be successfully applied at cement kilns.

The Chilled Ammonia Process (CAP) is also a chemical absorption process and very similar to the MEA process. Due to the lack of large-scale operational experiences the retrofitability of the CAP is rated slightly worse than the MEA process.

The MAL process is assessed very positive in most criteria, but the very early stage of development and the uncertainty of the suitability and robustness of membrane materials could be the decisive reason for many plant operators to exclude this technology from the tender procedures for the retrofit of a capture technology. Nevertheless, it could be a promising option in the future when more operational experiences will be available.

The retrofitability of both versions of the CaL process is evaluated differently. Whereas the retrofitability of the tail-end CaL process is seen suitable – with some uncertainties regarding the extent of the permitting process and the limited operational experiences – more attention is required for potential problems related to the integrated version of the CaL process. Especially the space demand of the required equipment close to the kiln line, the potential impact on the clinker production process and the missing operational experiences are currently drawbacks for an increasing use of this technology. Further investigations about the application of the CaL process are being carried out in an ongoing H2020 research project [5].

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 easier to retrofit than the more integrated technologies.

Finally it can be said that the future application of carbon capture technologies at cement kilns is dependent on further case-specific assessments of many different factors. Not only technical aspects (TRL, retrofitability) will play an important role, but also the costs, the political and legal framework for CCUS technologies will be decisive for the dissemination of carbon capture technologies and the meeting of climate targets.

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