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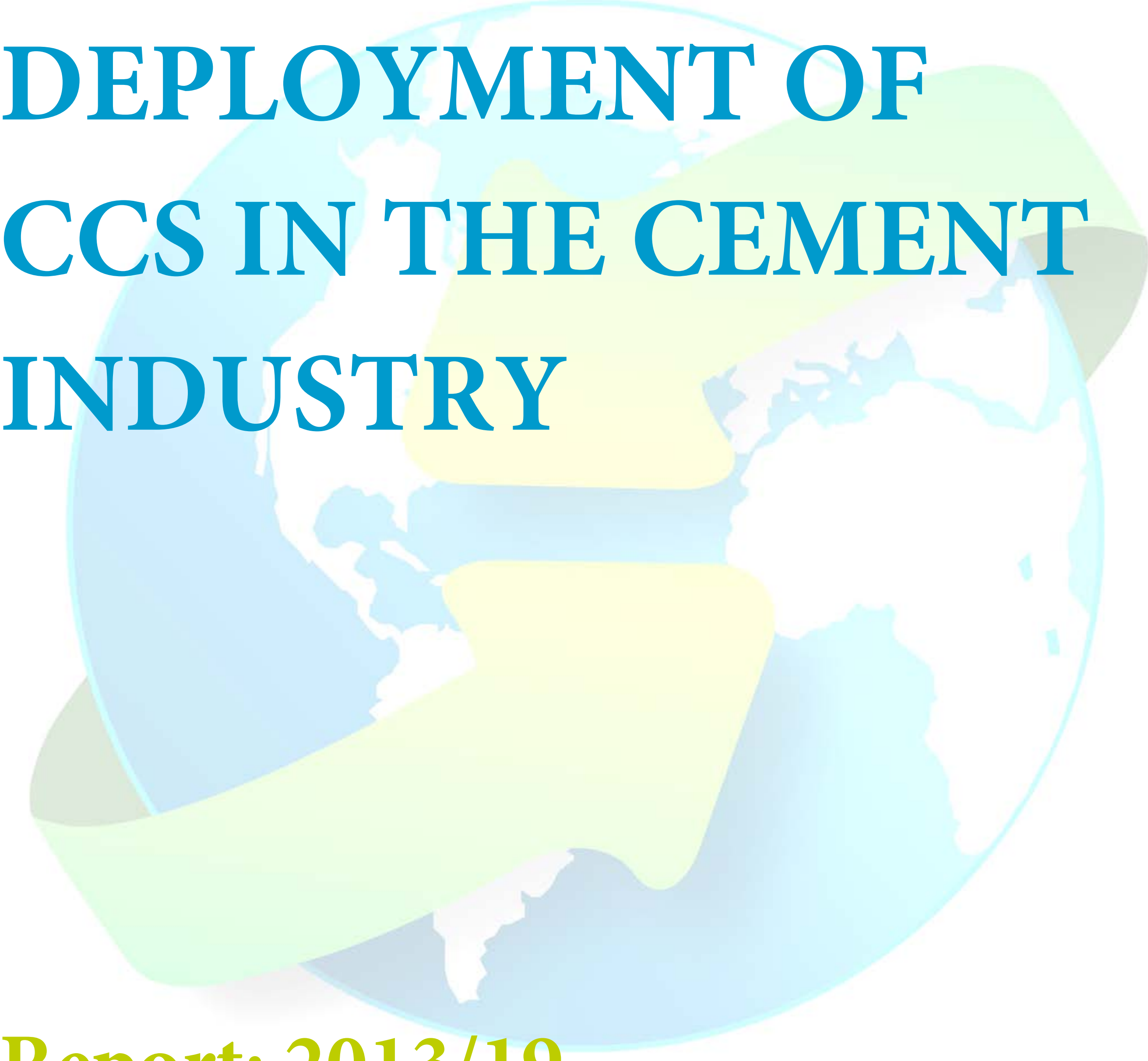

DEPLOYMENT OF CCS IN THE CEMENT INDUSTRY

Report: 2013/19

December 2013

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DEPLOYMENT OF CCS IN THE CEMENT INDUSTRY

Key Messages

- Established techniques can be used to reduce CO_2 emissions from cement production, including increased energy efficiency, use of alternative raw materials and fuels and reducing the clinker:cement ratio. However, CCS will be needed to achieve deep emission reductions.

- The preferred techniques for capturing CO_2 in cement plants are oxyfuel and post combustion capture. Pre-combustion capture is at a disadvantage because it is unable to capture the large amount of CO_2 produced by carbonate decomposition.

- Oxyfuel technology is in general expected to have a lower energy consumption and costs than post combustion capture using liquid solvent scrubbing.

- Some pilot plant projects for post combustion capture at cement plants are underway but oxyfuel technology for cement plants is still at the laboratory stage of development.

- A survey of the cement industry showed that most of the respondents think that CCS is relevant to them and they are aware of research projects, and half are involved in CCS activities. More than half of the respondents would contribute financially to CCS research but only a third would be willing to contribute to pilot or demonstration plants due to high costs.

- With the current legal and economic conditions CCS would impair the competiveness of cement production, which will inhibit development and application of CCS in the cement sector.

Background to the Study

The cement industry is a major source of industrial greenhouse gas emissions and accounts for around 5 % of global anthropogenic greenhouse gas emissions. The cement industry has been reducing its energy consumption and greenhouse gas emissions per tonne of cement through a variety of different techniques aimed at reducing costs and satisfying other environmental targets. These techniques have already been exploited to a significant extent and they will only be able to partly contribute to the emission reductions required to meet global climate change goals. The remaining fraction of the reduction will require the application of CCS.

IEAGHG published a techno-economic study on capture of CO_2 in the cement industry in 2008[1]. Since that time the level of interest in the application of CCS to cement production has increased but there is still relatively little practical development work being carried out. The main objective of this study is to review greenhouse gas emissions in the cement industry and provide a survey of the state of development and barriers to the deployment of CCS in this industry.

This study was undertaken for IEAGHG by the European Cement Research Academy (ECRA) in Germany, at the request of and with financial support from the Global CCS Institute (GCCSI).

Scope of Work

The study focuses on the following tasks:

1. Review current practice in energy efficiency improvement and fuel and clinker substitution practices in relation to reduction of CO_2 emissions in the cement sector.
2. Engage with key stakeholders with the aim of identifying the key barriers to the demonstration of CCS in the cement sector.
3. Review the current state of development of potential CCS technologies evaluated for the cement industry, particularly oxyfuel and post-combustion capture and review current CCS activities initiated and led by the cement industry.
4. Review policy and government initiatives to support the application of CCS to the cement sector.

Findings of the Study

State-of-the-art practice towards CO_2 reduction in the cement industry

Cement is a blend consisting mainly of ‘clinker’, along with various additives. In the state of the art clinker production process shown in Figure 1 raw meal consisting mainly of carbonate mineral, usually limestone, is pre-heated against hot flue gas in a series of cyclone preheaters. It is then fed to a precalciner when it is heated with fuel, resulting in the decomposition of most of the carbonate into calcium oxide and CO_2. The solid product from the precalciner is then fed to a rotary kiln where it is further heated by combustion of fuel and the calcium oxide reacts with silica and other minerals to produce the clinker product. The clinker is cooled, fed to a grinder and blended with other additives to produce cement.

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[1] CO_2 capture in the cement industry, IEAGHG report 2008/3, July 2008.

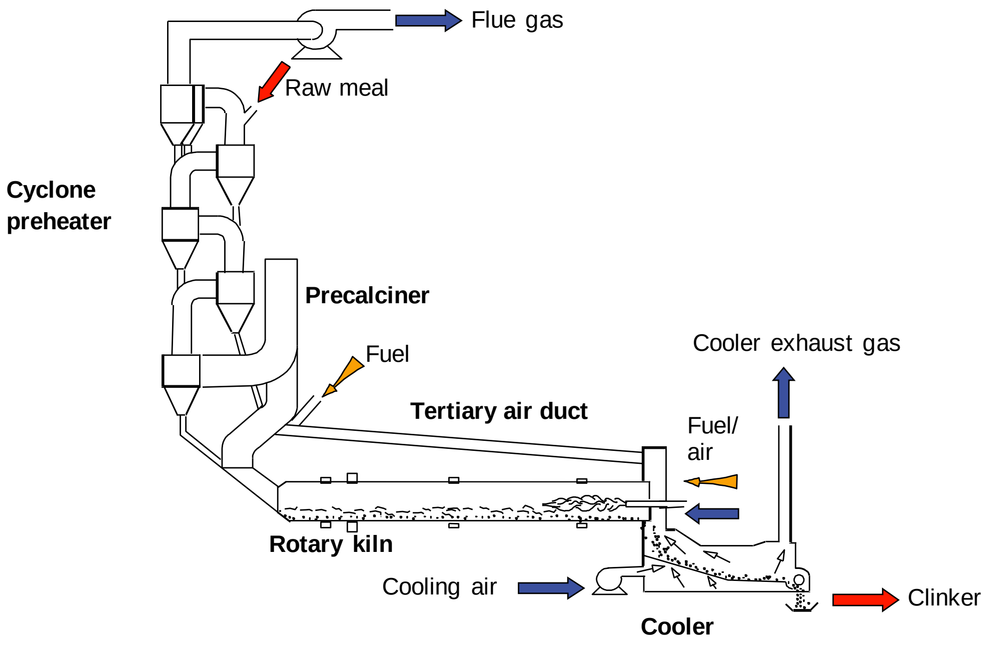

Figure 1 Cement clinker production plant

More than half of the CO_2 emissions from cement production are 'process related', i.e. from decomposition of carbonate mineral, and the rest are from fuel combustion. Apart from CCS, the main practices that can be used by the cement industry to reduce CO_2 emissions are:

- Increased energy efficiency
- Utilisation of alternative fuels
- Application of alternative raw materials
- A lower clinker:cement ratio

Increased energy efficiency

Just 64 % of the world's cement production is delivered by facilities which are equipped with precalciner technology and are working as described as state of the art practice. While a large number of cement plants with up-to-date technologies have been built in the last two decades, mainly in emerging countries, there is still a significant number of shaft, wet and semi-dry kilns as well as obsolescent grinding equipment in operation worldwide. Therefore, technical optimization of production processes offers a certain but limited improvement potential with respect to the energy demand.

In 2010 the thermal energy demand for cement clinker production was 3,580 MJ/t clinker[2] and the worldwide average electric energy demand for cement manufacturing was 108 kWh/t cement. According to ECRA's assessment the specific fuel demand can be reduced to a level

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[2] Worldwide weighted average, according to the World Business Council for Sustainable Development.

of 3,300 to 3,400 MJ/t clinker in 2030 and to 3,200 to 3,300 MJ/t clinker in 2050, i.e. around a 10% reduction by 2050. A fundamental change in the actual cement production technologies causing a significant reduction in the specific energy consumption is unlikely.

Utilisation of alternative fuels

Utilisation of alternative fuels, mainly derived from waste streams such as waste oil, tyres, plastics, mixed industrial waste, animal meal, sewage sludge, wood waste and grain rejects can reduce net CO_2 emissions due to their lower carbon content as well as their biogenic fraction. The overall CO_2 emissions of a cement kiln plant are not necessarily decreased and the thermal energy demand of the process may rise but biomass is carbon neutral when part of an ecological cycle with photosynthesis and recycle via combustion. Measures such as oxygen enrichment and gasification could partly compensate for the increased thermal energy demand but at the expense of higher electrical energy demand. In general, a lot of know-how is required in order to adapt the process to the differing properties of alternative fuels. This know-how exists in some world regions or companies but it is lacking in others. The importance of alternative fuels is growing globally due to other environmental advantages and positive economics. There are some investment costs, mainly for storage and handling and in some cases pretreatment but operational costs are lower due to lower prices of alternative waste fuels compared to regular fuels such as coal. In summary, the application of alternative fuels and other fuel switching offers the potential to contribute to the target CO_2 reduction requirement in 2050 by 24 % compared to the base case.

Application of alternative raw materials

The application of alternative raw materials can help towards the limitation of the process related as well as fuel related CO_2 emissions. CO_2 emissions can be reduced by using decarbonated materials because the CO_2 emissions have already been charged to the earlier processes that created them. Examples of alternative materials are wastes from recycled concrete or fibre cements and other materials such as blast furnace slag and fly ash. The limitations to this technique are mainly the availability of the alternative materials and the need to correct the composition of the raw material mixture to maintain product quality and kiln operation, which is only possible to a certain extent. Due to the limited availability of these materials, it is more reasonable to use them as clinker substitute in the cement because this enables higher emissions reduction potentials to be achieved.

A lower clinker:cement ratio

Cement is a blend of clinker, i.e. the material produced by a cement kiln, and other additives. A lower clinker-to-cement-ratio results in less energy demand for clinker production as well as less process CO_2 emissions due to the decarbonation of the limestone. The most important clinker replacing constituents are fly ash, slag, limestone and pozzolanas (a type of mineral of volcanic origin). It has to be taken into account, that the blended cements may have different or even limited cement properties compared to Ordinary Portland Cement but the greatest limitation is the availability of most of these materials.

Besides the approach to reduce the process CO_2 emissions by the reduction of the clinker content in cement or low-carbonate clinker, new binding materials as alternatives to cement, such as Celitement, Novacem or Calera are being investigated. However, these technologies are still at research or pilot scale. To what extent these materials could replace cement as binder in building materials is not currently foreseeable.

All of the techniques described above can contribute to a reduction of combustion and material related CO_2 emissions to a certain limited degree but the calculated potentials could not be simply added, as some of them counteract each other. Moreover some measures which enhance thermal energy efficiency require increased electrical energy demand and related indirect CO_2 emissions.

Nevertheless a simulated “blue map scenario” by IEA showed that 44 % of the target CO_2 reduction potential in the cement industry related to the base scenario in 2050 could be achieved by the conventional methods described above. This shows the prospects these methods still have but also the limits of the emission reduction potential.

Research and CCS activities in the cement industry

The preferred technologies for CO_2 capture in the cement industry are oxyfuel and post combustion capture. Pre-combustion capture is at a disadvantage because it would not capture the CO_2 produced by mineral decomposition.

Post combustion capture

Post-combustion capture technology has been the subject of research and has already been proven in some industries. Although part of this experience could be transferred to application in the cement industry, some issues especially concerning the cement plant’s flue gas composition and impurities still need to be proven at pilot scale.

Research activities that are currently on-going in the field of post-combustion capture include chemical absorption, adsorption, membrane, mineralization and calcium looping technologies. The most investigated technology is chemical absorption but this faces the challenge of a high energy demand. Developments in calcium looping or membrane processes may have the potential to increase the overall energy efficiency but further research and development is needed. There would be some synergies between calcium looping and a cement plant because the purge stream of de-activated calcium sorbent could be reused as raw material in the cement clinker production process.

Pilot and demonstration plant projects which are actively proceeding include:

Norcem, Brevik, Norway***:*** Test centre offering the possibility to conduct several small scale or pilot trials of post combustion capture using cement plant flue gas (2013-2017). Companies involved in this project include Aker Solutions (amine scrubbing), RTI (dry adsorption with specialized polymers), KEMA, Yodfat and NTNU (membranes) and Alstom (calcium looing).

ITRI/Taiwan Cement Corp.: Pilot plant capturing 1 tonne CO_2/h from a cement plant and a power plant using a calcium looping process, commissioned June 2013.

Skyonic Corp.: Plant under construction, capable of capturing 83,000t CO_2/y from a cement plant in Texas, using the “SkyMine” process. In this process salt and water are electrolyzed to produce hydrogen and chlorine gases and sodium hydroxide solution, which is reacted with CO_2 in flue gas to produce sodium bicarbonate, which can be sold on the market. Other combinations of chemicals can also be produced.

Due to the already high level of knowledge, the technology of post-combustion capture has the potential for implementation in a relatively short timescale, but not before 2020 for full scale plants.

Oxyfuel

Unlike post combustion capture, oxyfuel technology requires adaptation of the cement clinker production process. Oxyfuel technology for cement production is still at the basic research and laboratory testing state of development. Detailed research is still needed before advancing to pilot-scale, which is the next logical step but currently no pilot plants are planned or initiated. As a pre-stage, ECRA is presently preparing a concept study for an oxyfuel pilot cement kiln. The time horizon for application of oxyfuel technology at several full size cements plants is expected to be not before 2025.

Hybrid technologies

Hybrid technologies in terms of a combination of oxygen enrichment and post-combustion technologies have not been actively investigated. The benefit of those combinations depends on several factors concerning the energy demand, which interact with each other. Therefore it is not possible at present to make reliable statements on technical and economic barriers and potentials.

Stakeholders’ opinion on CCS

Cement industry stakeholders were surveyed by way of a questionnaire to determine their awareness, activities, interests and reservations about CCS.

Figure 2 shows the characterization of the participating stakeholders. The main feedback was given by companies from Europe, Middle East, Asia and North America. The greatest number of participants were cement producers but plant manufacturers, gas suppliers, technology providers and research centres also provided feedback. Approximately half of the companies are global players with international businesses. In summary the composition of the responding companies delivers a representative overview of the industry’s view on CCS technologies.

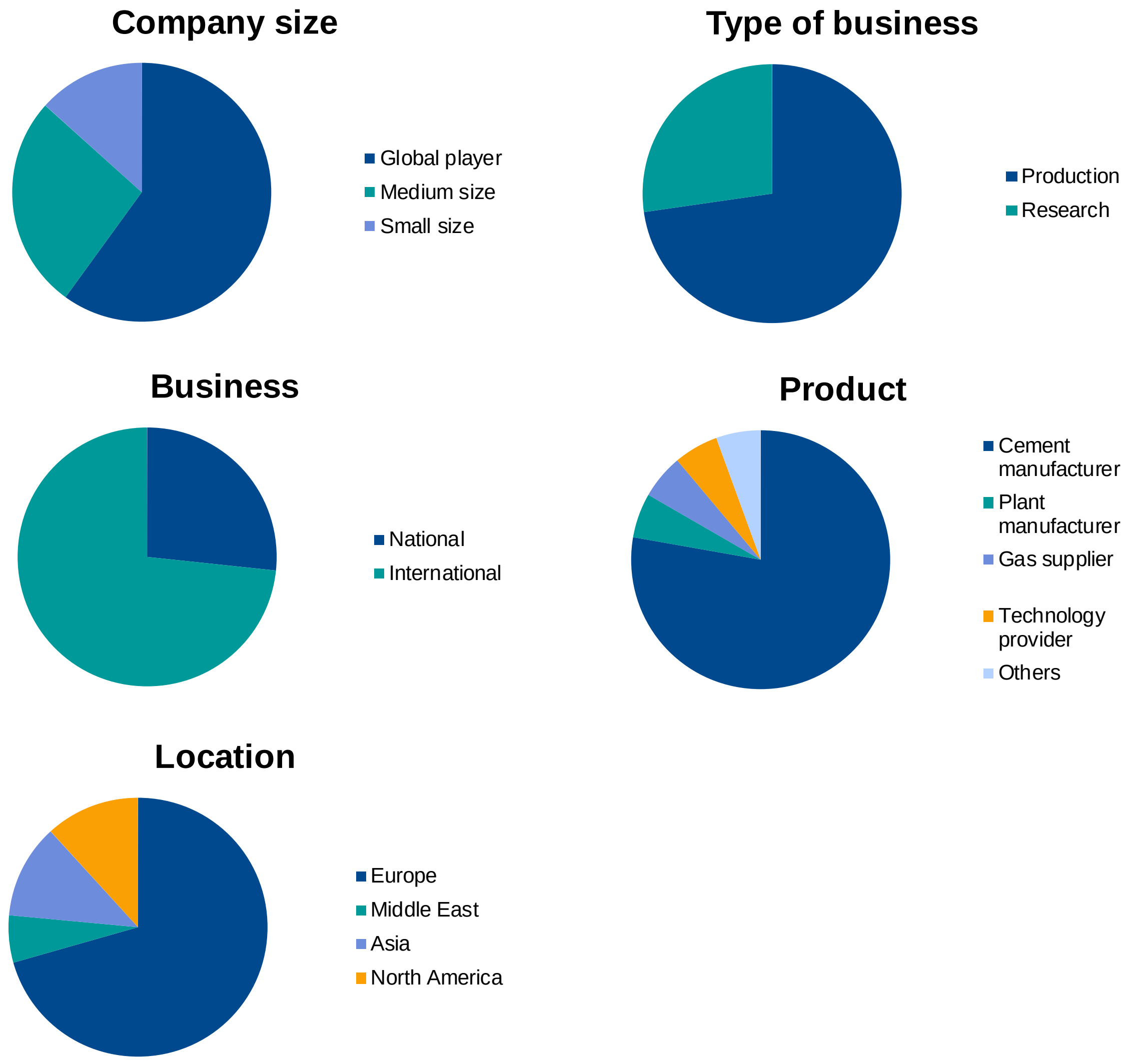

Figure 2 Companies responding to the stakeholder survey

Evaluation of the questionnaire showed the following main results:

- Most repondents are aware of CCS technologies but the knowledge about CCS and the activities in this field is lower in the Middle East and Asia than in Europe.

- Approximately three quarter of the responding companies feel CCS is a relevant issue or an issue which will become relevant for them. Especially medium or smaller sized cement producers and plant manufacturer think that CCS is not relevant for them at this stage of development. Uncertainties about the technical feasibility and the avoidance of economic risk make them prefer tradional methods for CO_2 reduction.

- Nearly half the respondents, especially from Europe, are involved in CCS activities, mainly as part of a consortium with or without financial contribution. Most of the companies are at least aware of these research projects.

- Nearly 90 % of respondents think that these technologies have potential in the cement industry and would apply them, if they were available. The negating companies are those which are convinced of other technologies or too alienated by the uncertainties of the technical feasiblity (including medium sized companies and plant manufacturers). Also some companies are not aware of capture technologies but they would apply them, if they became state of the art.

- More than half of the interviewees would contribute financially to research but only about a third would contribute to a pilot or demonstration plant due to high costs. The willingness to financially contribute to research or especially to pilot or demo plants is higher in globally acting companies.

- Alternatives to CCS for CO_2 reduction are seen in about 40 % of respondents and some 10 % are uncertain about the development of other technologies for emission control.

Technical and economic performance

The study evaluated the technical and economic performance and barriers to application of oxyfuel technology and post-combustion capture using chemical solvent absorption in cement plants.

Technical issues relating to the use of chemical solvent absorption for post combustion capture in cement plants are largely the same as for power plants. These include the possible need for secondary treatment to reduce the quantities of impurities such as SOx, NOx, particulates and other trace materials in the flue gas to avoid excessive degradation of the solvent and the need for disposal of degraded solvent waste. Space and HSE requirements may also constitute a constraint at some plants. The solvent reboiler consumes a large amount of energy and as there is only sufficient waste heat in a cement plant to provide about 15 % of this energy demand, an additional combined heat and power (CHP) plant is needed. The CO_2 emissions from the CHP plant can be captured along with those from the cement plant. Two CHP options were considered in this study: a coal fired boiler plant and a natural gas combined cycle (NGCC) plant. The optimum choice will depend on local conditions and fuel prices.

Oxyfuel technology can be integrated in the clinker production process using two different concepts – full or partial oxyfuel. In the partial oxyfuel concept, oxygen is used only in the pre-calciner and the rotary kiln remains air-fired. In the full oxyfuel concept oxygen is used in both the precalciner and the kiln. Both concepts seem likely to be suitable for retrofitting existing plants, although the plant specific space availability in the structure may limit the construction. As integrated systems, both concepts influence the process and the material conversion and greater effort will be required for operating and controlling the plant. Enhanced HSE measures will be required for handling high purity oxygen and carbon dioxide. While the thermal energy demand is only affected to a small extent, the electrical energy demand is doubled per tonne of cement product.

Figure 3 compares the Total Plant Costs (i.e. excluding owner's costs, interest during construction and start-up) of a reference plant without CO_2 capture and various plants with capture. The costs are for European plants producing 1Mt/y of clinker (1.36Mt/y of cement). The costs of the plants with post combustion capture are higher particularly because of the need to build a combined heat and power plant to supply steam for regeneration of the capture solvent. It should be noted that the capture rate in the partial oxyfuel case is about 60% compared to 90% in the other cases.

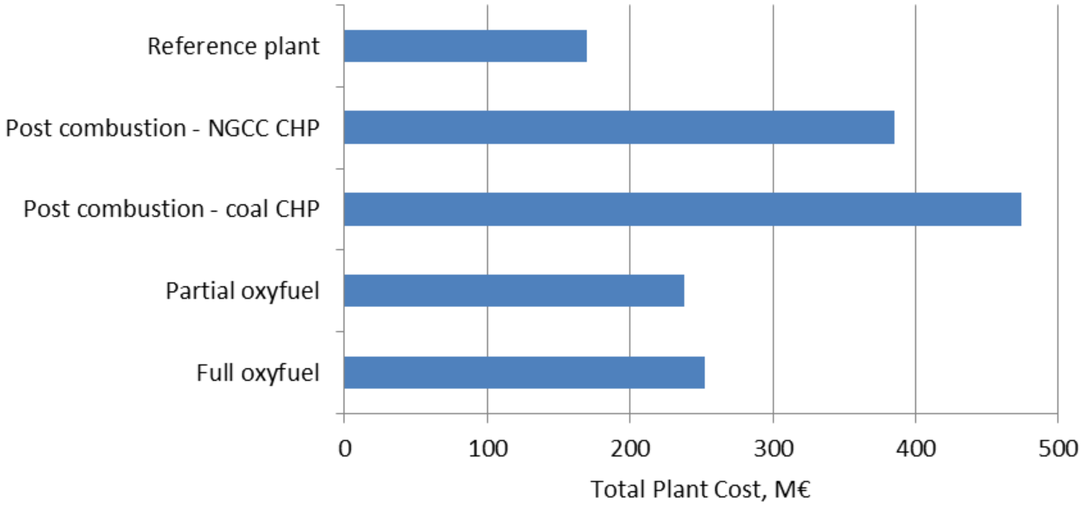

Figure 3 Comparison of Total Plant Costs

Figure 4 compares costs of cement production. The costs are based on coal and gas costs of 3 and 6 €/GJ respectively, an 8% discount rate, a 25 year plant life, an 80% annual capacity factor and an electricity value of €80/MWh, which is an approximate average of the costs of power generation with CCS in coal and gas fired power plants in recent IEAGHG studies. Details of other technical and economic assumptions used for these cost estimates are included in the study report.

The cement production cost is increased by 68-105% when applying post combustion capture and 36 to 42% when applying oxyfuel technology. In the case of the oxyfuel technologies this cost increase is mainly driven by the additional electricity demand, whereas the main costs for post-combustion capture are both additional electrical and fuel energy demand as well as the at least doubled investment cost. It should be noted that costs are subject to significant uncertainty and will depend on various factors including site specific conditions, fuel prices and future technology developments. These costs exclude CO_2 transport and storage costs. Cement plants are normally located close to the source of limestone and have relatively small CO_2 outputs compared to power plants, which would tend to increase CO_2 transport and storage costs. However, if the plant was close to other sources of captured CO_2, a larger trunk pipeline could be used which would reduce costs. As an illustration of the impact of transport and storage costs, a cost of €10/t CO_2 stored would increase the cost of cement production by about €5/t for the full oxy-fuel case.

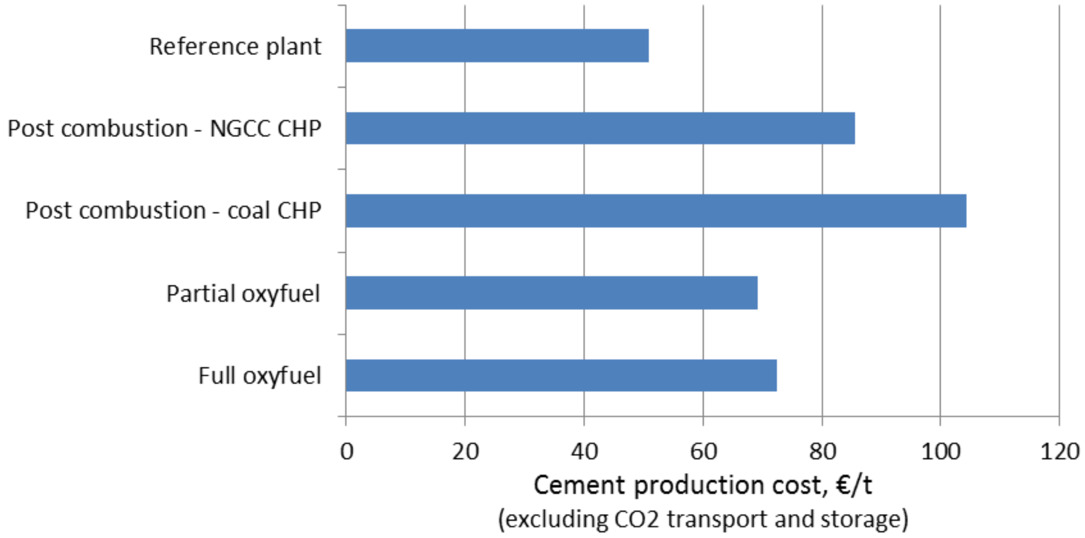

Figure 4 Comparison of cement production costs

The cost of avoiding CO_2 emissions depends on the definition of the quantity of emissions avoided. Different definitions could be used for cement plants with CCS:

- The direct emissions avoided at the cement plant site;
- The direct emissions plus the indirect emissions from power plants at other sites.

Oxy-fuel cements plants import electricity generated at other power plants, mainly for oxygen production and CO_2 compression. If this electricity is generated at power plants which emit CO_2, these ‘indirect emissions’ reduce the quantity of emissions avoided by CCS at a cement plant. In contrast, plants with post combustion capture would normally require an on-site CHP plant to provide the low pressure steam for CO_2 capture solvent regeneration. The CHP plant would generate some electricity from passing high pressure steam through a back-pressure turbine and, in the case of an NGCC, from a gas turbine. This electricity is usually sufficient to provide all of the needs of the capture plant and there is a surplus, which displaces power that would otherwise be generated in external power plants. Including indirect emissions therefore increases the quantity of emissions avoided for cement plants with post combustion capture.

The cement industry’s preferred definition of the quantity of CO_2 emissions avoided is the ‘direct’ emissions, because those are the emissions which a cement plant operator would be accountable for, and for which they would have to pay CO_2 taxes or purchase emission credits.

The quantity of indirect emissions depends on the specific CO_2 emissions of the electricity system. At the time when CCS is installed on a large scale at cement plants, electricity generation may already be mostly decarbonised, in which case the ‘indirect’ emissions would be small.

Direct costs of CO_2 emission avoidance compared to the reference plant, excluding costs of CO_2 transport and storage, are shown in Figure 5. Including indirect emissions, assuming the same electricity value and specific emissions of 600 kg CO_2/MWh, would decrease the cost of emissions avoidance of post combustion capture by 9-14 €/t and increase the cost of oxyfuel by 4-6 €/t CO_2.

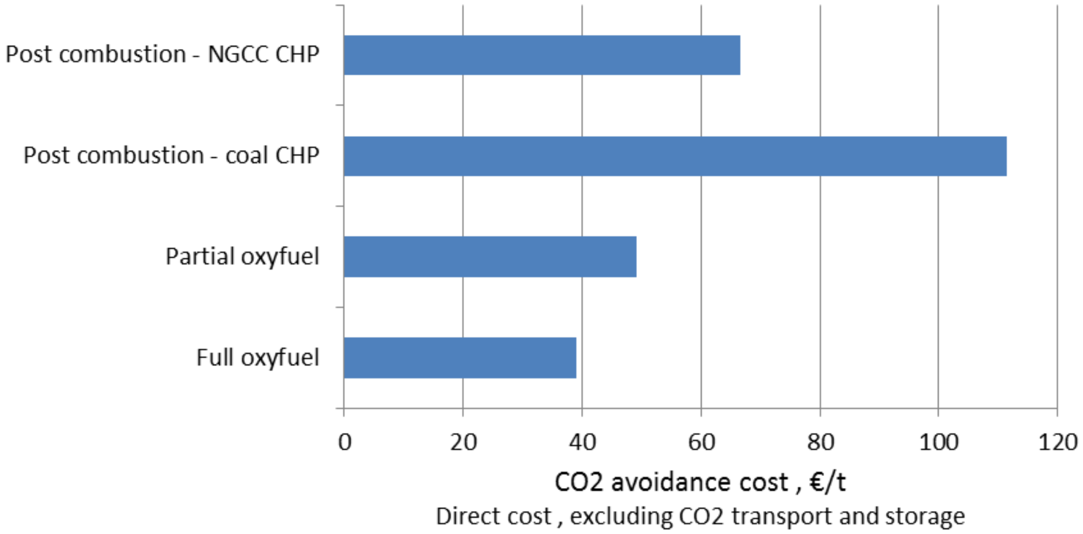

Figure 5 Comparison of CO_2 avoidance cost

The full oxyfuel technology shows the lowest cost of CO_2 avoidance. Regarding post-combustion capture, the combination with an NGCC CHP plant is less costly than a coal fired CHP plant, but this depends strongly on the relative prices of coal and gas.

Other studies have shown that a symbiosis of a cement plant with power plants and a joint CO_2 capture plant (carbonate looping) could reduce the specific costs of post combustion capture.

Sensitivities to various technical and economic criteria were assessed in the study. In particular, because global cement production is concentrated in less developed countries, the sensitivities of costs to two non-European locations, China and the Middle East, were assessed. CO_2 avoidance costs in these regions were estimated to be around 50% lower than in Europe.

Barriers to CCS in the cement industry

The overall investment costs and the operational costs are seen as a high barrier to initiate even the first steps towards pilot and demonstration plants. Any time frame for either of the technologies will therefore to a high degree depend on substantial funding. Specific funding for carbon capture demonstration and research in the cement industry is not available.

From today’s perspective, with respect to the current legal and economic conditions CCS technologies would impair competiveness of cement production. Some nations or groups of countries have put a price on CO_2 emissions (via cap-and-trade or tax) to stimulate investments in emission reduction methods such as CCS. Since the costs for CCS and the corresponding CO_2 price are high as a proportion of the cement production cost there is always a significant risk that clinker and/or cement will be imported from countries with lower abatement costs, with the corresponding carbon leakage. This must be taken into account in designing the appropriate legal framework for CO_2 abatement by means of CCS in the cement industry.

Further generic barriers to CCS are the lack of an adequate overall legal framework for CO_2 storage and inadequate storage capacities in some countries.

In conclusion there seems to be little incentive to undertake the high effort to build a CCS installation without a dedicated political approach which addresses the risk of carbon leakage and a clear perspective towards reliable storage options.

Expert Review Comments

Comments on the draft report were received from seven reviewers in the cement industry and research and energy policy organisations.

A general view of the reviewers was that the report provided a good contribution to knowledge in the subject area. Key suggestions included a request for more information on the economic analysis and more detailed and up to date information on calcium looping, which were addressed in the main study report, along with various other detailed comments. The length of time required for commercial demonstration was questioned by some reviewers and consequently discussion of this issue was expanded.

Conclusions

Established techniques can be used to reduce CO_2 emissions from cement production, including increased energy efficiency, use of alternative raw materials and fuels and reducing the clinker:cement ratio but these techniques are already being used to a significant extent. The scope to further reduce emissions using these techniques is therefore limited.

A survey of the cement industry, including cement producers, equipment suppliers and others has shown that most of the respondents think that CCS is relevant to them and they are aware of research projects, and half are involved in CCS activities, mainly as part of a consortium. More than half would contribute financially to research but only a third would be willing to contribute to pilot or demonstration plants due to high costs.

The preferred techniques for capturing CO_2 in cement plants are oxyfuel and post combustion capture. Post combustion capture is considered to have the potential for application in a shorter timescale because of relevant experience in the power sector but tests at cement plants will still be needed to determine the effects of the different flue gas compositions. Some pilot plant projects using various technologies are underway. Oxyfuel technology is still at the laboratory stage of development and there are currently no firm plans for pilot and demonstration plants.

This study indicates that oxyfuel technology will have a lower energy consumption and costs than post combustion capture using liquid solvent scrubbing. However, costs of CCS at cement plants still have relatively high uncertainties due to the absence of real plant data and site specific factors, in particular the various options for supply of steam for post combustion solvent scrubbing. Also, new technologies may in future reduce the costs and energy consumptions of CO_2 capture at cement plants.

The current globally unequal cost of emitting CO_2 would impair the competiveness of cement production with CCS. There is a significant risk of import of cement or clinker from countries with lower abatement costs, with corresponding carbon leakage. Underdeveloped legal frameworks for CO_2 storage in some countries are a further constraint on the development and application of CCS technologies in the cement sector.

Recommendations

It is recommended that IEAGHG should continue to maintain a watching brief on CCS in the cement industry as part of its portfolio of activities on CCS in sectors other than power generation.

A further techno-economic assessment of oxyfuel technology, conventional post combustion capture and next generation capture technologies including calcium looping and membranes should be undertaken when or if sufficient information becomes available from operation of the cement industry pilot plant projects described in this report. This study could also include a more detailed assessment of options for providing the additional energy for post-combustion solvent regeneration, either by an additional power source on-site (coal or NGCC CHP) or in combination with a nearby power plant (cluster arrangement).

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Deployment of CCS in the Cement Industry

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Deployment of CCS in the Cement Industry

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Executive Summary

This study “Deployment of CCS in the cement industry” summarises the current activities on CO_2 capture and storage (CCS) in the cement industry and gives an overview of the prospects and limitations of this technology for cement kilns. The focus of the study is on CCS deployment in Europe. As the study’s empirical basis key stakeholders were questioned about their opinion on CCS in order to identify the key barriers to its exploitation. A large fraction of the respondents see a potential for CCS technology for future CO_2 reduction, and the willingness to apply the technologies is high. However, many concerns, in particular with regard to technical and economic feasibility, were highlighted. In addition, uncertainties originating from the current legal framework and political developments were named as barriers to the further development of CCS. More R&D and pilot/demonstration testing, together with their financial support, are seen as key issues with regard to overcoming these concerns. On the other hand, the willingness to contribute financially to pilot/demonstration testing appears to be limited to some globally operating companies. As a consequence of the technical and economic CCS barriers short term measures for CO_2 emission reduction are mainly seen in the further development of existing cements. New cements and binding materials are currently under development or undergoing research. Their application is not expected to significantly substitute Portland cement clinker in the coming years.

In relation to the deployment of CCS and the reduction of CO_2 emissions in the cement sector, the current practices in; energy efficiency improvement; alternative fuel / raw material use; and, clinker substitution practices were reviewed to form the study baseline scenario. The reduction potential is described for a reference plant located in Europe and its operational mode. All of the technologies described may contribute to a reduction of combustion and/or process-related CO_2 emissions, but their individual reduction potentials cannot simply be added together because of their interaction as some of them counteract each other.

In terms of energy efficiency improvement through modernisation, today’s potential is already being exploited to a great extent. As a consequence investment costs for remaining, limited improvement potentials are very high. Fundamental changes in cement manufacturing technology are also unlikely as seen from today’s technical perspective.

Through the utilisation of alternative fuels and biomass, anthropogenic CO_2 emissions can be reduced due to their lower carbon content or their biogenic fraction, which can be considered ‘carbon neutral’. In general, when alternative fuels are utilised, considerable experience is required in order to adapt the process to the differing fuel properties. This experienced knowledge exists in some world regions or companies, whereas it is less well developed in others. The importance of alternative fuels is growing globally due to positive economic and environmental aspects. The application of alternative raw materials can help towards the limitation of process-related, as well as fuel-related, CO_2 emissions. By utilizing waste materials, natural resources can be preserved and the sustainability of cement manufacture can be increased. However, depending on the region and type of materials so-called alternative fuels may be very limited in their availability which as a consequence limits the respective substitution rate in cement manufacturing. The use of alternative materials and industrial by-products as a clinker substitute in cement provides for high reduction potentials in terms of fuel and process CO_2 emissions. However, depending on their composition these cements may have different cement properties as compared to ordinary Portland cement which in turn may limit their application to certain construction projects.

The development of CCS in the cement industry has been initiated in recent years through different research studies and laboratory tests. In general, capture technologies like post-combustion capture and oxyfuel technology seem to be more appropriate for potential application at cement kilns than others. Therefore, in this study, oxyfuel technology (full and partial) as well as post-combustion capture by means of chemical adsorption have been evaluated in terms of technical and economic barriers. The key parameters and potentials of both technologies are summarised in **Table 1-1**.

Table 1-1 Oxyfuel and post-combustion capture technology – a comparison as applied in the cement industry

Issue	**Oxyfuel Technology**	**Post-combustion capture**
Concept	Integrated concept	End-of-pipe technology
Effect on cement kiln operation	Process and material reaction is influenced	Minimal impact on existing cement kiln process
Development status	Oxygen enrichment has been applied to cement kilns Oxyfuel-technology still requires some R&D	Commercially available in other industry sectors Pilot-scale testing in cement industry initiated
Time horizon for commercial application at several full size plants	not before 2025	not before 2020
CO_2 purity	CO_2 from the combustion (~ 85 vol.%) process is concentrated and purified in CO_2 purification unit (CPU)	Pure CO_2 stream for compression (90 -99 vol.%)
Applicability to existing plants	Retrofitting is feasible with modifications at the kiln plant Space requirement for ASU/CPU Existing plant structures have to allow the integration of Oxyfuel infrastructure	Retrofitting is possible and no kiln redesign is required High space requirement for capture plant and power generation
Energy demand	High electricity demand for CPU and ASU resulting in a doubling of power demand per tonne of cement produced Thermal energy demand could be reduced	Very high energy consumption for solvent regeneration resulting in a doubling of electrical and thermal energy demand per tonne of cement produced
CO_2 avoidance costs (direct emissions)	40 – 50 €/t CO_2	65 – 110 €/t CO_2

Post-combustion technology as an end-of-pipe solution has been the subject of research and has even been proven in some industries in the past few years but still needs to be adapted to the clinker burning process (e.g. in terms of flue gas composition).

Different research activities in the field of chemical absorption, adsorption, membrane, mineralization and calcium looping technologies are currently on-going. The most investigated technology is chemical absorption, which faces the challenge of a high energy demand for the reboiling of the solvent.

As a modern cement plant does not provide sufficient excess waste heat, an additional power plant (CHP or NGCC) to operate the capture process is needed. This leads to additional CO_2 emissions, which have to be simultaneously captured. Due to this high energy demand the cement production costs are increased by at least two thirds and could even be doubled.

Developments in calcium looping (CaL) or membrane processes may have a higher potential to increase the overall energy efficiency and therefore further reduce the specific CO_2 capture costs. In the case of calcium looping in particular the problem of waste sorbent disposal can be solved as deactivated sorbent from the CO_2 capture could be reused as raw material in the cement clinker production. Solid purges from calcium looping systems of power plants could also be supplied to the cement process as alternative raw material (pilots exist for approval of CaL systems in power plants: La Pereda, University of Darmstadt and Stuttgart). For these reasons membrane and calcium looping technology should be investigated in pilot plants which have currently been initiated (e.g. Brevik, Taiwan Cement, Skyonic projects).

Technical issues to be addressed for the use of chemical absorption for CO_2 separation are mainly the flue gas composition in terms of SO_2 and NO_x and trace components, which harm the solvent in higher concentrations and might require secondary abatement techniques.

In addition to space and Health & Safety requirements the treatment or disposal of waste solvents can be a constraint. From a purely technical point of view and based on the already high level of available knowledge, post-combustion technology is being discussed as a capture method which could be implemented in the short term. However, a first full-scale post-combustion installation in the cement industry will not be able to operate before 2020, which is necessary to fulfill EU climate change aspirations by 2050.

Oxyfuel technology is still at a basic research stage, because the integration of the technology influences the process and the material conversion in the kiln. This technical constraint means that the cement kiln needs to be completely redesigned in a new installation or at least requires significant adaptations of existing plants. However, studies have shown its suitability for retrofitting existing plants, although the plant-specific space availability in the structure may limit constructive implementation. The complexity of operating and controlling such a plant will be greater especially due to the handling of pure oxygen and carbon dioxide. While the thermal energy demand is only slightly affected or even decreased, the electrical energy demand is doubled per tonne of produced cement. This power demand in particular leads to higher operating costs which are the main contributor for the 50% increase of production costs. Based on different research studies the starting point for further R&D has been laid, but more detailed research is still needed before advancing to a pilot-scale, which is the next logical step. Currently no pilot plants are planned or have been initiated using oxyfuel technology in the cement clinker burning process. As an oxyfuel cement installation will require more time to gain experience in pilot and demonstration plants it is not envisaged that a first full scale plant would operate before 2025. Only after this date more full-scale application in the cement sector could be envisaged.

The overall investment costs and the subsequent operational costs are seen as a significant barrier to implementation of the first pilot and demonstration plants. Any time frame for either one of the technologies will therefore to a high degree depend on substantial funding. Specific funding for carbon capture demonstration and research in the cement industry is not available with only a few funding programmes that are broadly focused on CCS demonstration in the industry for example the US ARRA programme.

Table 1-1 also underlines the economic barriers which inhibit the development of carbon capture technologies in the cement sector. With respect to the current legal and economic conditions these technologies would impair competiveness in cement production due to the globally unequal cost for emitting CO_2. Some nations, regions or groups of countries have put a price on CO_2 emissions (via cap-and-trade or tax) and many of which aim to stimulate investments in reduction methods such as CCS by increasing the cost of emitting. Since the costs for CCS and the corresponding CO_2 price are very high there is always a significant risk that clinker and/or cement are imported from countries with lower abatement costs with the corresponding carbon leakage. Especially today the risk is high since prices for CO_2 pollution allowances are lower than the additional capture costs. Furthermore, even if prices would increase as a consequence of changing political rules, the additional costs of emitting CO_2 would have to be borne by the operator until technical abatement measures like carbon capture would be implemented. This must be taken into account in designing the appropriate legal framework for CO_2 abatement by means of CCS.

Another barrier, however, is the missing legal overall framework for CO_2 storage and the lack of storage capacities. Some nations or groups of countries have initiated different approaches to providing the necessary regulatory framework to ensure that CO_2 will be safely and permanently stored underground, for example the EU CCS directive or the US permitting guidance. Other nations, such as India, have underdeveloped CCS initiatives primarily because geological capacity for CO_2 storage is limited and are instead focusing on the reuse of CO_2 (Carbon Capture and Use) for example in algae or Enhanced Oil Recovery.

In conclusion there seems to be little incentive to undertake such an extremely high effort to build a CCS installation without a dedicated political and economic approach which addresses the risk of carbon leakage and has a clear solution for reliable storage options.

Against this background the reuse of CO_2 might provide better prospects for CO_2 capture in the cement industry. Power to gas projects, for example, have been initiated and might provide a good link between energy storage and CO_2 utilisation. To what extent such combined technology synergies will be technically and economically feasible for cement manufacture remains open at this time. The review of these groundbreaking indicative studies outlines the potential of such an approach but also underline the need for further research in this field.

Düsseldorf, 31 January 2014

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1 Introduction

The cement industry is a major source of industrial greenhouse gas emissions and contributes to around 5% of the global anthropogenic greenhouse gas emissions. In order to address the environmental imperative of climate change the International Energy Agency modelling indicates that the energy related CO_2 emissions have to be cut in half from the current levels by 2050 [IEA-13]. As part of this global reduction the IEAGHG has estimated that, in a baseline scenario which includes today's policies and the forecasted market development, the cement industry will need to reduce its CO_2 emissions from 2.34 Gt to 1.55 Gt (i.e. 34%) [IEA-09/2].

The cement industry has reduced its production related (specific) greenhouse gas emissions over the last two decades through a combination of different programs aiming at economic and ecological targets.

The potential of the technologies that are commercially available now, such as increase of energy efficiency, reduction of clinker content in the cement as well as application of alternative fuels, have already been exploited to a certain extent. Hence, these reduction technologies will only partly contribute to the emission reductions required. The remaining fraction of the reduction, being some 56%, will require the application of carbon capture technologies. Thus worldwide capture shall need to achieve a level of 25% of the total CO_2 emissions within the cement sector by 2050 [IEA-13]. According to [IEA-13] the CCS technology has to be demonstrated before 2020, to clear the way for commercial application by 2030. By then approx. 6% of the generated CO_2 shall be captured by CCS technologies. If the international reduction goal for 2050 shall be met, 50% of the European cement works would have to apply CCS measures [IEA-09].

The application of CCS requires the separation of the CO_2 from the process. Different separation techniques, such as post-combustion or oxyfuel technologies, are being discussed for application in the cement industry. The purified CO_2 stream can then be compressed and could either be geologically stored (CCS) or reused (CCR). The storage of CO_2 requires appropriate sites, e.g. depleted gas/oil fields or saline aquifers. Long distances may separate suitable storage sites and cement plants, and an appropriate transport system will need to be developed. The CO_2 could also be re-used as a feedstock in chemical manufacturing or used in Enhanced Oil Recovery (EOR).

1.1 Scope of the study

Against this background this study summarizes the activities, prospects as well as limitations of CCS/R in the cement industry. In accordance with the specifications of IEAGHG the evaluation focused on Europe; a sensitivity analysis for a limited number of other world regions is included. Specifically, the aims of this study focus on the following:

1. To review current practice in energy efficiency improvements, fuel switching, and clinker substitution practices in relation to deployment of CCS and more generally the reduction of CO_2 emissions in the cement sector.
2. To review the current state of development of potential CCS technologies in the cement industry. Particularly, this study will focus on post-combustion, oxyfuel combustion and calcium looping technology.

3. To engage with key stakeholders with an aim to identify the key barriers to the demonstration of CCS in the cement sector.
4. To review current CCS activities initiated and led by the cement industry. To provide a listing of activities at research, pilot and demonstration scale that are currently on-going and an estimation of the timeline for commercialization of CCS in the cement industry.
5. To review policy and government initiatives that support the application of CCS in the cement sector.

The study is therefore structured as follows:

Chapter II: Summary of the key stakeholder’s opinion

Chapter III: Establish baseline, analysis and review of the state-of-the-art practices towards CO_2 reduction

Chapter IV: Identification of suitable CCS systems for the cement industry and current activities in this field

Chapter V: Technical and economic assessment of the CCS technologies

Chapter VI: Review of policies and initiatives to support CCS deployment in the cement industry

1.2 Cement and its production

Cement, as binder of concrete, is a construction material that sets automatically as a consequence of chemical reactions with water and subsequently retains its strength and soundness both when exposed to air and submerged in water. Cement consists of finely ground Portland cement clinker and calcium sulphate (natural gypsum, anhydrite or gypsum from flue gas desulphurisation). In addition, cement may contain other main constituents, such as ground granulated blastfurnace slag, natural pozzolana (e.g. trass), fly ash, burnt oil shale or limestone. **Figure 1-1** depicts the manufacturing process schematically. What is known as Portland cement clinker is made from a raw material mix mainly consisting of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (alumina (Al_2O_3)), and iron oxide (Fe_2O_3). These main constituents, which form the latter clinker phases and define the cement reactivity, are supplied by limestone, chalk and clay or their natural blend, lime marl. Limestone and chalk are composed of calcium carbonate ($CaCO_3$), whose decomposition is responsible for the major fraction of the process generated CO_2 emissions. Cement has a specified quality requirement so a precisely defined raw material composition must be complied with for the cement to attain its specified properties (e.g. strength). Only a small margin of deviation can be tolerated.

The raw material mix is heated up to a temperature of approximately 1,450 °C in a rotary kiln until it starts sintering. This results in the starting materials forming new compounds known as clinker phases. These are certain calcium silicates and calcium aluminates which confer on the cement its characteristic features of setting in the presence of water.

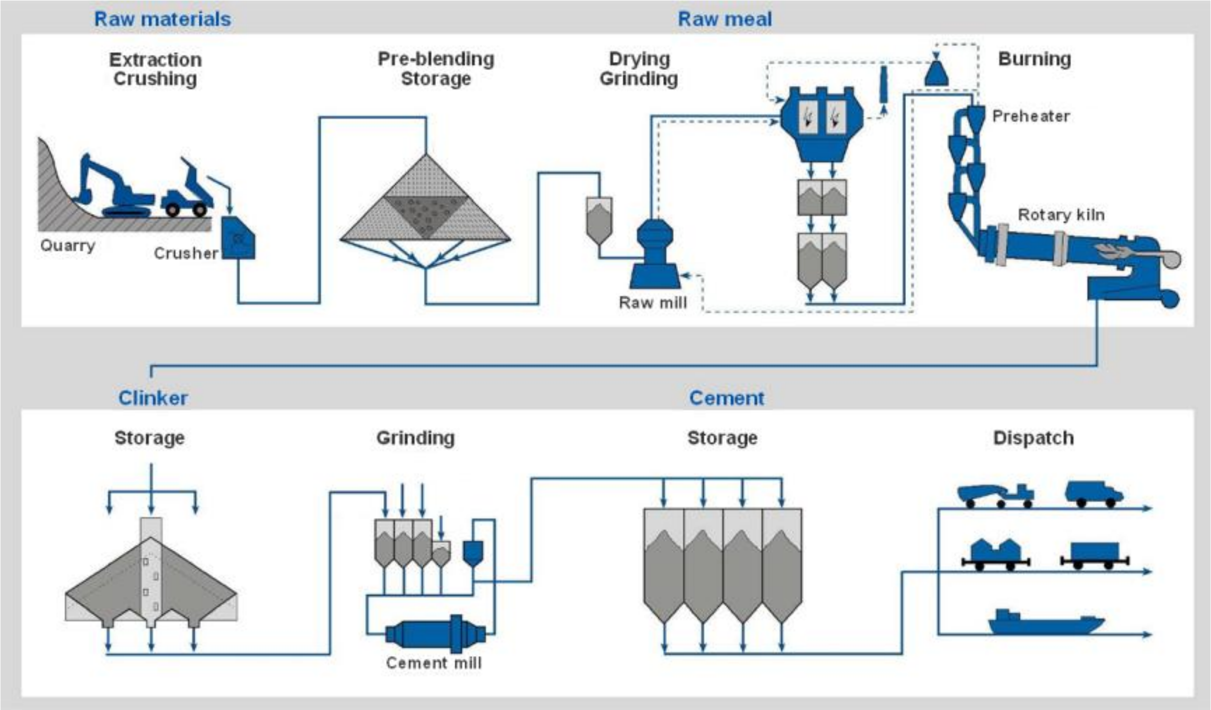

Figure 1-1 Cement manufacture

The clinker burnt in the rotary kiln is subsequently ground to cement in finish mills with calcium sulphate, which enhances the workability of the cement. If necessary, further main constituents are added, which modify the setting of the cement or have favourable effects on the physical properties of the concrete.

In Europe the cement clinker is mainly produced by the ‘dry process’ by rotary kiln systems with cyclone preheaters. Basically the process is operated on the counter-current principle of gas and material. The preheater consists of three to six stacked cyclone stages. The kiln feed is fed into the gas duct of one stage, entrained by the gas during which it is heated, and finally collected in the cyclone. It then drops into the gas duct of the next lower stage, is heated further by the gas, and is collected again.

Modern plants are equipped with a precalciner system, which is mostly constructed as a riser duct between preheater and kiln. The supply of the fuel is divided between the two firing systems in the precalciner and main burner in the kiln. Using a precalciner allows over 90 per cent of the calcium carbonate to have reacted prior to entering the kiln. In precalciner kilns up to 60% of the fuel is consumed in the precalciner.

The precalcined material is dropped into a rotary kiln, where it passes counter-current to the hot gases. During this process the material is heated from about 900°C to 1,500°C, during which the chemical and mineralogical transformations necessary for cement clinker formation take place. The necessary energy is provided by the combustion of fuels, which are injected by the primary air at the main burner. The fuel energy released in the kiln is transferred to the kiln feed, both directly by radiation from the flame and indirectly via the kiln wall.

The task of the clinker cooler is to cool the cement clinker in continuous operation to the lowest possible temperature. This temperature regime is adapted to suit the specified product quality. At the same time, the combustion air required for the burning process is preheated to achieve the lowest possible use of fuel energy. The preheated gas, which is supplied to the kiln, is named secondary air. The so-called tertiary air is preheated gas that bypasses the kiln to be used as combustion air to the precalciner.

1.3 Definition of the reference case scenario

The reference case relies on the Best Available Technique (BAT) standard as defined in the European BREF-Document (**B**est Available Technique **Ref**erence). The plant structure for the reference case based on a dry kiln process consists of a five stage cyclone preheater, precalciner with tertiary duct, rotary kiln and grate cooler as illustrated in **Figure 1-2**.

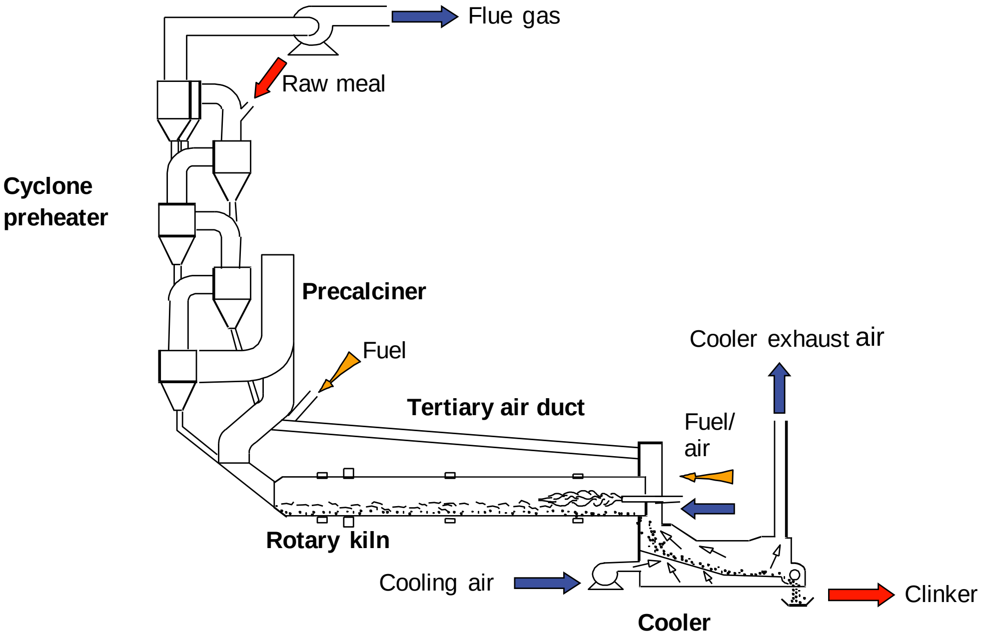

Figure 1-2 Principle of a BAT standard cement kiln plant

In accordance with the specifications of IEAGHG the focus of the evaluation centred on Europe. An average production capacity of 3,000 t/d (1 Mt clinker/y) was chosen as this is a representative size of cement plants in Europe. The characterising values are of the reference case plant are based on different data acquisitions of the cement industry [CSI-09, GNR-10, McK-08] in Europe and specification of the IEAGHG (further detail can be found in Annex 8.2). The specifications for the reference plant are summarized in **Table 1-1**.

The specific fuel consumption is determined on the basis that the European average alternative fuel input is approximately 30 per cent of fuel energy input. Start-ups and shut-downs are included in an annual average of 3,280 kJ/kg clinker [Kle-06]. This value was estimated on the assumption of a BAT plant without bypass operation, which is the same technology as used in the reference plant.

Due to the required temperature level of 900°C in the precalciner, fuels of lower calorific values can be utilized. Therefore especially extreme wet fuel types like drained sewage sludge can be applied as alternative fuel. In the sintering zone the higher temperature level requires a fuel type at the main burner at LHV above ca. 20,000 kJ/kg, which could be derived from dried materials like RDF. Low average heating values (LHV) of 20,000 kJ/kg for alternative fuels in the main burner and of 16,000 kJ/kg for alternative fuels combusted in the precalciner are assumed [Kle-06]. Coal at 27,000 kJ/kg (LHV) is used as the fossil fuel basis. For economic reasons natural gas or oil is primarily used for start-ups and its overall yearly portion is therefore relatively small. As the normal operation of the plant will be evaluated, these fractions of fossil fuels have been neglected.

Table 1-1 Specifications for the reference plant (source: see Annex 8.2)

BAT-Reference plant – general assumption	
Technology standard	BAT (calciner, tertiary air duct, 5-stage cyclone preheater, modern grate clinker cooler)
Location	Europe
Production capacity	1 Mt clinker/y (3,000 t/d)
Cement production	1.36 Mt cement/y
Clinker/cement factor	73.7%
Raw meal/clinker factor	1.6
Spec. fuel consumption	3,280 kJ/kg clinker
Regular fossil fuel	69.5%
Alternative fuels	26%
Biomass	4.5%
Spec. total electricity demand	97 kWh/t cement
Spec. electricity for clinker production	65 kWh/t clinker
Raw material moisture	6%

The electrical energy demand is attributed to the operation of kiln gears, fans and conveyors but the main contributors are mill drives. Focussing on the clinker production, namely the kiln plant and its auxiliaries, the power supply of 65 kWh/t clinker (ca. 48 kWh/ t cement) is required. The finish grinding of clinker and other constituents to cement needs additional power, which doubles the demand of electrical energy for cement production to 97 kWh/t cement. Indirect CO_2 emissions derive from this onsite electricity demand up to approx. 10% of the cement related CO_2 emissions (average 0.06 t CO_2/t cement).

In the cement industry greenhouse gas emissions relate to process and fuel CO_2 emissions. Process-related CO_2 results from the decomposition of raw material components and additives. These emissions account to two thirds and fuel-related to one third of the total CO_2 emissions. **Table 1-2** shows the specific CO_2 emissions of the cement production for the reference case. The direct CO_2 emissions are described for the reference case and its boundaries, which is considered as a BAT-plant. Boundaries for the evaluation of the direct CO_2 emission value are the energy demand and 30% substitution rate of alternative fuels. These values are comparable to the best 20th percentile of the European average of 3,314 kJ/kg clinker and 0.818 t CO_2/t clinker [GNR-10]. Although these European average values could not be assigned to a certain operational mode in the same way as the reference plant with its reference operation. For this reason the above specific plant value of 0.828 t CO_2/t clinker (excl. biomass) is taken because this value is directly linked to the named operational boundary conditions of the reference plant (energy demand, substitution rate, plant specifics etc.). Excluding the biogenic fraction of the alternative fuel mix the lowers the specific CO_2 emissions as outlined in **Table 1-2**. Furthermore, the reference plant operational mode does not include the inefficiencies of start-ups and shut-downs, which ideally occurs only once a year during the annual planned plant maintenance (approx. three weeks of stoppage), although occur more frequently in reality due to unplanned maintenance.

Table 1-2 BAT-Reference plant – CO_2 emissions

Reference plant – CO_2 emissions	
CO_2 from electricity	0.5 - 0.7 t CO_2/MWh
Spec. indirect CO_2 from electricity	0.049 - 0.068 t CO_2/t cement
Spec. direct CO_2 from clinker production (incl. biogenic CO_2)	0.828 t CO_2/t clinker (based on 30 % substitution by alternative fuel mix, compare **Table 1-3**)
Spec. direct CO_2 from clinker production (excl. biogenic CO_2)	0.804 t CO_2/t clinker (based on 30 % substitution by alternative fuel mix, compare **Table 1-3**)
Total spec. CO_2 emissions incl. electricity	0.66 – 0.68 t CO_2/t cement

When using alternative fuels it is possible that a certain amount of generated CO_2 is classified as biogenic. Depending on the fraction of biomass, this biogenic CO_2 content can differ. **Table 1-3** summarizes the biogenic fractions assumed for the different types of alternative fuels. The fuel mix is based on the distribution in **Table 1-1**. The biomass fraction of 4.5% consists of substances originating from wastes like animal meal and sewage sludge. Cultivated biomass, which is used in some industries requiring certain qualities, is usually not applied in the cement industry. A further assignment within the biomass is not required for the following considerations. The European alternative fuel input [GNR-10] is divided by thermal energy into 19.4% tyres, 11.7% solvents/waste oil, 12% domestic wastes and 56.9% pretreated industrial wastes.

Table 1-3 Biogenic fractions of alternative fuels

Alternative fuel type	Biogenic fraction	Typical LHV
Animal meal	100%	18 MJ/kg
Sewage sludge	100%	4 MJ/kg
Pretreated domestic wastes	50%	16 MJ/kg
Pretreated industrial wastes (plastics, textile, packaging)	30%	18 – 23 MJ/kg
Tyres	27%	28 MJ/kg
Solvents, oil residues	0%	23 – 29 MJ/kg

In accordance with European legislation (Industrial Emissions Directive, IED) the following emission limits are required to be met using each of the assessed CO_2 reduction techniques.

Table 1-4 Reference – emission limits (related to 10% oxygen content)

Emission limits	
SO_2, mg/m^3_{STP}	50*
NO_X, mg/m^3_{STP}	500**
C, mg/m^3_{STP}	10*
Particulates, mg/m^3_{STP}	30

* Exemption depending on raw material possible

** Exemption for long and Lepol kilns to max. 800 mg/m^3_{STP} until 01st Jan 2015 possible

The reference for the economic assessment and the economic boundary conditions are given in section 5.1.

1.3.1 Reference: Worldwide situation

Global clinker production has increased worldwide during recent years especially in emerging economies. In 2011 only 22 per cent of the global production was in Europe where the production capacity is decreasing. Although Europe was selected as a reference region in this study a limited comparison to other regions in the world is included in a sensitivity assessment. For that purpose the differences of the process data and costs are shown in **Table 1-5** and **Table 1-6** based on average values (not reference). As no reference plant is defined for the worldwide market, the average values are taken for the sensitivity analysis.

Table 1-5 Process comparison Europe (EU28) and worldwide [GNR-10]

	Europe (EU 28)	**Worldwide (incl. Europe, China, India, Middle East)**
Average thermal energy input, precalciner/preheater kiln	3,620 kJ/kg clinker	3,400 kJ/kg clinker
Average thermal energy input, all kiln types	3,730 kJ/kg clinker	3,580 kJ/kg clinker
Spec. direct CO_2 from clinker production	0.862 t CO_2/t clinker	0.858 t CO_2/t clinker
Electrical energy input	117 kWh/t cement	108 kWh/t cement
Clinker/cement factor	73.7%	76%
Precalciner/preheater kilns	44% (of clinker capacity)	64% (of clinker capacity)
Dry process kilns	81% (of clinker capacity)	83% (of clinker capacity)
Fuel substitution rate	30.5% (of thermal input)	12% (of thermal input)

In general the average thermal energy demand for the cement production worldwide is lower compared to Europe. This mainly arises as emerging economies such as China and India, which are major global cement producers, have installed a large number of precalciner plants of higher capacity in recent years.

The clinker to cement (cli/cem) factor is varying between worldwide regions due to different standards and the specific requirements on the cement depending on the regional conditions (e.g. climate). Principally the cli/cem factor in Europe is lower compared to China, India or Middle East.

The energy prices and availability also differ by economic region, this will be included in the sensitivity analysis. The economic assumptions are shown in **Table 1-6**.

Table 1-6 Cost comparison Europe and worldwide [McK-08]

	Europe	**Worldwide (incl. China, Middle East)**
Labour costs (yearly)	60.000 €/FTE*	5 – 17.000 €/FTE
Employee per plant	100	150 - 300
Electricity price	80 €/MWh	20 – 60 €/MWh
Coal price	80 €/t	40 – 70 €/t
Alternative fuel price	15 - 25 €/t (15 – 30% of coal price)	
Natural gas	6 €/GJ	6 €/GJ

* FTE: Full Time Employee

2 Stakeholder's opinion on Carbon Capture

The following section illustrates the stakeholder opinions towards CCS technologies within the cement industry as well as related or supplying industries (such as plant manufacturer, gas suppliers, CCS technology providers) in order to identify the information gaps further research requirements and current activities. Using a survey questionnaire, companies from different regions, sizes and business have been interviewed about their awareness, activities, interests and reservations about CCS (see **Table 2-1**). Based on the results an overview of stakeholders' opinion has been elaborated.

Table 2-1 Questionnaire

Question No.	
1	Are you aware of CCS Technologies?
2	Is this a relevant issue for you?
3	Do you perform any activities in the field of Carbon Capture?
4	if yes: Please, specify activities
5	if yes: Amount of invest?
6	if yes: What was the intention?
7	Do you know from any activities in the cement industry?
8	if yes: Please, specify activities
9	Do you think CCS has a potential in the cement industry?
10	Would you apply CCS technologies, if they are available?
11	What requirements must be given to apply CCS?
12	Are you willing to contribute financially to a pilot or demo plant?
13	Are you willing to contribute financially to research?
14	In your opinion, what are the main open questions?
15	How can answers be found?
16	What are the main constraints?
17	Do you think there are any alternatives to CCS?

Figure 2-1 shows the characterization of the participating stakeholders. The main feedback was given by companies from Europe, Middle East, Asia and North America. The main fraction of companies are cement producers, which are attributed to the high percentage of production business. Additionally, plant manufacturers, gas suppliers, technology providers and research centres are also included in the stakeholder's opinion. Approx. half of the questioned companies are global players in international businesses. In summary the composition of the responding companies delivers a broad overview of the industry's view on CCS technologies.

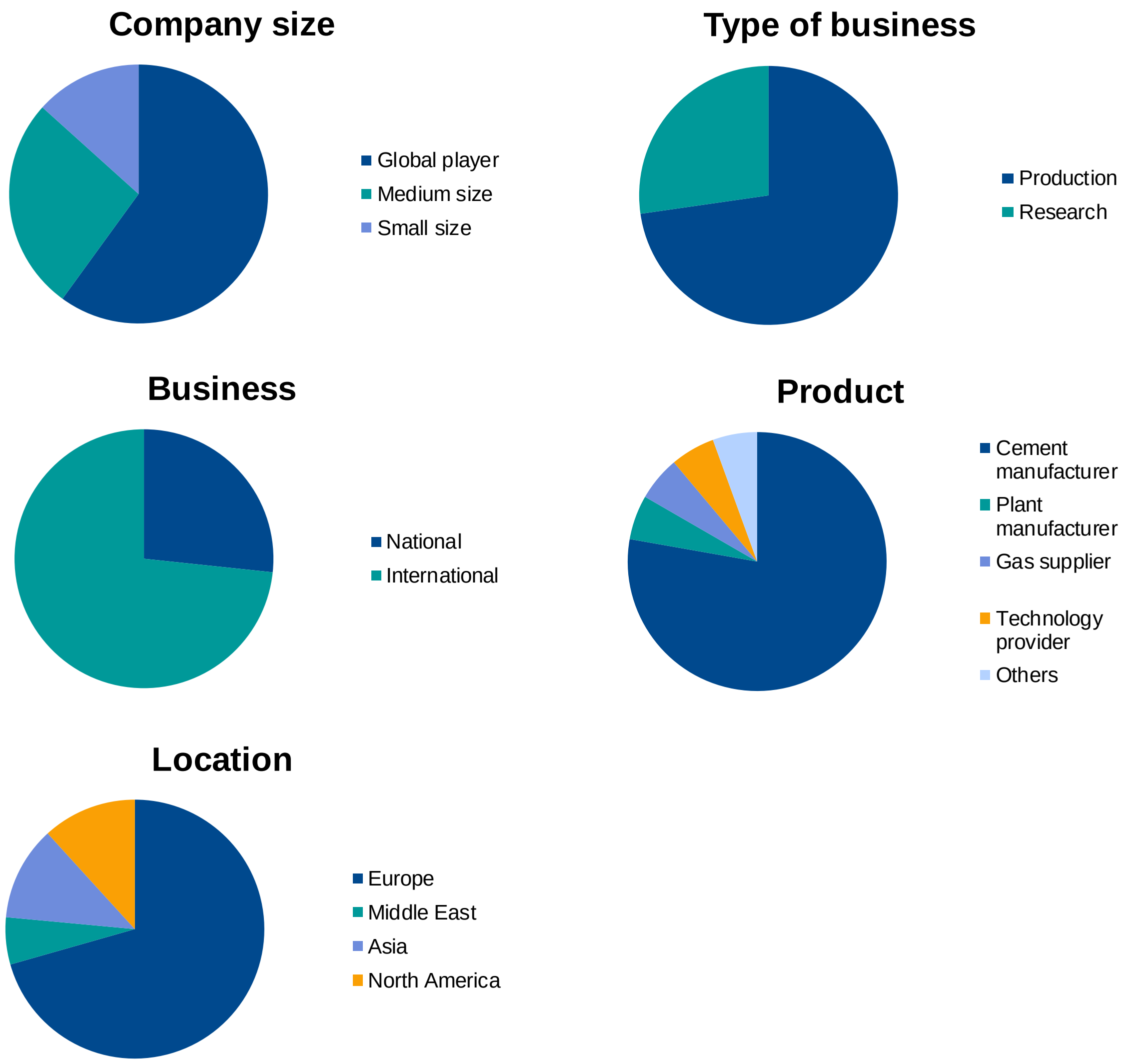

Figure 2-1 Information on responding companies

Some companies and associations have already issued official statements on carbon capture technologies in the cement industries.

- The Mineral Products Association, UK stated that cement is essential for economic and social development. Beyond the effort of reducing the carbon footprint by traditional methods in the UK, especially with regard to raw material related CO_2 emissions, two solutions are identified for the future.

  “In the short term, the industry is doing all it can to reduce the amount of natural raw material it needs to calcine and new ‘novel’ low carbon cements are beginning to emerge but are still some way off production. The long term possibility is to capture CO_2 emissions and lock them away in geological formations forever.

  Nevertheless, the cement industry does consider CCS to be a long term possibility and is investing in research and development to see if, how and when the technology can be applied to clinker production. It is important to note, however, that capture technologies can only be useful when the full chain of CCS is available, including transport infrastructure, access to suitable storage sites and a legal framework for CO_2 transport and storage, monitoring and verification, and licensing procedures. …

It is unlikely that CCS technologies in the cement industry will be deployed before 2025… The UK cement industry looks forward to playing its part in this long term vision." [MPA-13]

- The globally active cement company CEMEX stated "CEMEX sees CCS as a potential mid-term solution to limit carbon emissions, and will continue to pursue all funding opportunities for the advancement of this technology. Nevertheless, even under the most optimistic scenario, we do not expect to conduct a first industrial-scale project at one of our plants in the near term. To a large extent, whether CCS can live up to its promise will depend on governments and society as a whole. Public funding for well-designed research and development projects, the necessary political developments, and open and transparent discussion with our stakeholders about the pros and cons of CCS will be required." [CEM-12]
- In a similar way HeidelbergCement as an international cement producer pointed out, that "CCS enables industry to further minimize emissions to meet future demands". HeidelbergCement/Norcem pilot CCS (post-combustion) project "aims to determine the viability of CCS as a solution for future handling of carbon dioxide emissions at our cement plants." [HEI-11]
- Moreover the Colombian cement producer Cementos Argos has positioned the company in favour of CCS. "Argos believes that the future of cement production as the industry now knows it will change significantly." This company sees their "Cement plant of the future" as an oxyfuel kiln. Thus "one of the changes envisaged by the company is CO_2 management, for which the recirculation and concentration of CO_2 will be key."[BER-12]

In addition to these official statements the evaluation of the questionnaire showed the following main results (summarized in **Figure 2-2**):

- Most repondents are aware of CCS technologies but the knowledge of respondants about CCS and the activities in this field is lower in the Middle East and Asia compared to Europe.
- Approximately three quarters of the responding companies feel CCS is a relevant issue or an issue which will become relevant for them. Medium or smaller sized cement producers and plant manufacturer think that CCS is not relevant for them at this stage of development. Uncertainties about the technical feasibility and the avoidance of economic risk make them prefer traditional methods for CO_2 reduction.
- Nearly half the respondents, especially from Europe, are involved in CCS activities, mainly as part of a consortium with or without financial contribution. Most of the companies are at least aware of these research projects.
- Nearly 90% of respondents think that carbon capture technologies have potential in the cement industry and would apply them, if they were available. The remaining 10% of respondents are those which favour other technologies or are discouraged by the uncertainties of the technical feasiblity of CCS. The respondents in this group included medium sized companies and plant manufacturers. Also some companies are not aware of capture technologies but they would apply them, if they became available

- More than half of the interviewees would contribute financially to research but only approx. 35% would contribute to a pilot or demonstration plant due to the high costs. The willingness to financially contribute to research or especially to pilot or demo plants is higher in globally acting companies.
- Alternatives to CCS for CO_2 reduction are seen in about 40% and some 10% of interviewees are uncertain about the development of other technologies for emission control.

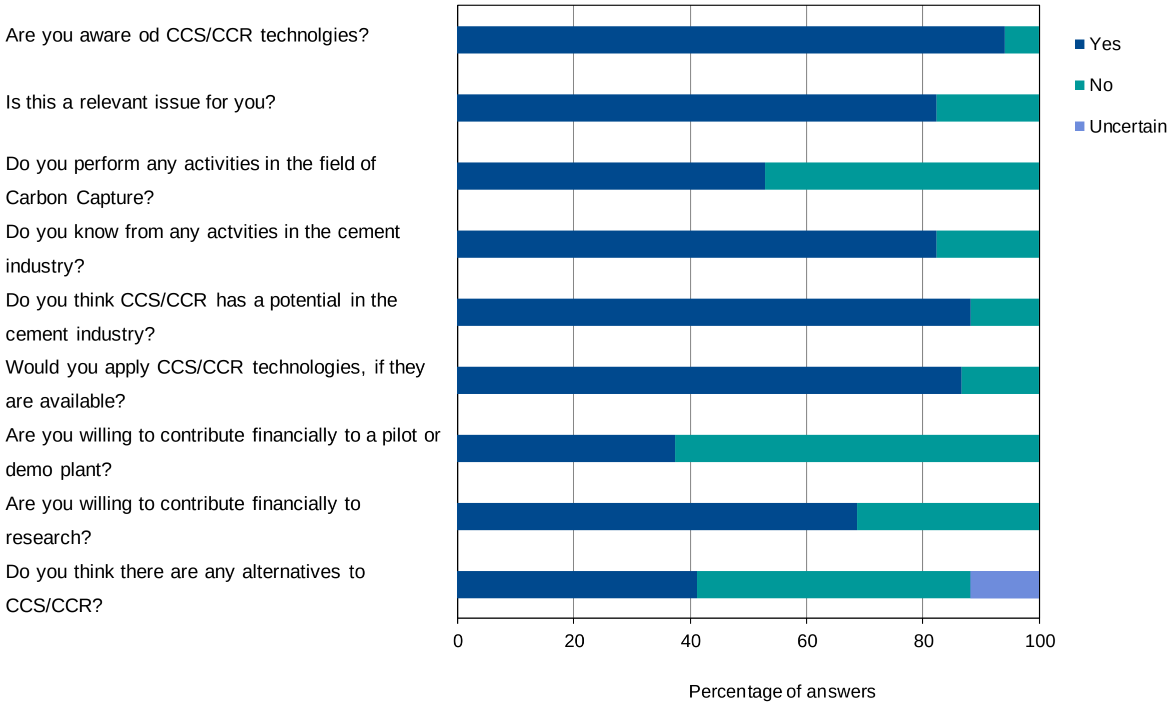

Figure 2-2 Evaluation of the questionnaire

This evaluation can be summarised by the following statements:

Why are CCS technologies relevant for you?

Yes (82%), because:

- Cement industry is one of the biggest emitting sectors, so CO_2 emission reduction is important.
- No breakthrough technologies for further CO_2 reduction are expected.
- No other technology is capable to handle the emission reduction targets in case a global agreement is signed under the auspices of UNFCCC[1].
- Economic interest as technology provider
- Self-imposed requirement due to the expectation of an undersupply of freely granted pollution certificates (EUA) in the next years.
- Traditional methods are limited
- There is a need for exploitation of all possible technologies for CO_2 reduction

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[1] United Nations Framework Convention on Climate Change

- Inclusion of GHG emissions in the NSR/PSD[2] regulations and permitting

No (18%), because:

- Realisation is uncertain
- Complexitiy of operation (more chemical plant than cement production)
- Counteracting the current effort to increasing energy efficiency and conserving resources
- Business planning required for the technology is too far in the future

Do you perform any activities in the field of Carbon Capture?

Table 2-2 Questionnaire: Activities in the field of Carbon Capture

Current activities	Company	Sector	Budget/ Contribution	Intention
ECRA Research Phase IV.A (Europe)	Consortium	Cement	1.4 M €	Keep track on carbon capture development Support technology development Development of a pilot plant Ensure that the cement industry is prepared
Norcem project implementing post-combustion technology (Norway)	Cement producer	Cement	12.5 M €	Support technology development
Oakbio project in California, microbes test facility (USA)	Technology provider / Gas supplier	Cement	Advice	Support technology development
Field test on injection and geological storage (USA)	Technology provider / Gas supplier	CCS	Participation	Support technology development
Demonstration on OTSG for oil sand industry (USA)	Technology provider / Gas supplier	Power	Participation	Support technology development
Oxy-coal testing (USA)	Technology provider / Gas supplier	Power	Support of University Utah	The experimental program focusses on the amount of flue gas recirculation to achieve adequate heat transfer and on combustion issues with oxygen enriched flue gas recirculation.

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[2] New Source Review and Prevention of Significant Deterioration permit regulations (USA)

Current activities	Company	Sector	Budget/ Contribution	Intention
Engineering studies on ASU/CPU technologies and on demonstration of oxy-coal tech. at 50 MW boiler (USA)	Technology provider / Gas supplier	Power	Participation	Support technology development
Bench and pilot scale development of near zero emissions CPU for oxyfuel fired furnaces (USA)	Technology provider / Gas supplier	Power	$ 5.4 MM co-funded by DOE	Identify large scale technical and engineering issues for oxygen supply and CO_2 purification and the costs for CCS
CapCO2, ACACIA, France Nord, European Mustang project. (France)	Cement producer	CCS	Participation and Sponsoring	Prove of principle
Industrial teaching and research chair on CCS at le Havre university and the Mining School of Paris (France)	Cement producer	Cement	Co-Founder	Further development of the technology and identification of costs
Developing innovative technologies like Carbonate-Looping (Italy)	Cement producer	Cement	Cooperation with Politecnico di Milano	Evaluation of costs to develop innovative technologies, which can also be applied to regular production line.

What requirements must be given to apply CCS?

- Technical viability of cabon capture in the cement industry as well as transport and storage at a reasonable price
- Long-term testing of this technology (~5 years)
- Destination for CO_2
- Global agreement to set minimum price for CO_2 (UNFCCC)
- Funding for projects to scale-up the technology
- Competitiveness of the industry has to be ensured due to higher production prices. Thus initiatives should be introduced to minimise trade impacts
- Clear political and legal frame for implementation
- Public acceptance
- Political pressure for further reduction or even governmental directive to apply CCS technologies
- Clarification of uncertainties
- Recycling capacities of CO_2 for reuse

- Presence of steady market forces over long planning horizon to drive investment decisions
- Financial requirements like investment and payback period
- Validation of safety of the clinker production process concerning health and environment
- Low risk and/or liability for negative ancillary impacts on the environment

In your opinion, what are the main open questions?

- Technology development in the cement industry especially concerning retrofit (e.g. air tightness of the process)
- Economical feasiblity (CO_2 penalty higher than CCS costs). Actual (cement) industry crisis is an obstacle for the collection of the necessary economic resources.
- Legislative framework
- What to do with the CO_2? Possibilities for non-volatile storage or for reuse.
- Who is responsible for the stored CO_2 in long-term?
- Requirements on transport (e.g. CO_2 purity and pipeline quality specifications, pipeleine networks)
- How to involve other nations and transfer technology to them
- Market situation: Is the end customer willing to pay increased product costs?
- Compatibility with local infrastructure situation
- Global willingness for further GHG reduction

How can answers be found?

- Research and development and pilot plants (on capture and storage)
- Financial support by governments for R&D and demonstration plants
- Business question will be solved by establishing the political framework
- Clear communication to politicians and public regarding the impact CCS may have on the construction industry
- Cross-sectoral cooperation
- Reduction of the capture taget of 100% e.g. to 50%

What are the main constraints?

- Economic and technical feasibility
- Costs of CCS demonstration projects – lack of funds
- Guarantee of competitiveness of front runners
- Low carbon prices
- Uncertainness about the role of CO_2 in the context of climate change
- Convincing industry managers, governments and public about the neccessity of CCS due to the lack of information e.g. on legislative regulations

- Public acceptance
- Although a lot of engineering is needed the product is not enhanced (cement is of same quality)
- Storage (e.g. tectonic setting, geothermal regimes etc.)
- The cooperation between different industrial activities create the problem of the intellectual property of the ideas.

Do you think there are any alternatives to CCS?

No (50%), because:

- Energy conservation, energy efficiency and alternative energy sources can partially offset the need for CCS but they can not eliminate the need for CCS as long as fossil fuels are consumed.
- Traditional reduction methods will never achieve the reduction level of CCS technologies
- Currently not, but CCS technologies are seen as transitional technologies until others will be found in order to produce hydraulic binders at a large scale and competitive price as today.

Yes (40%), because:

- Reduction of product related CO_2 emissions by clinker substitution, new binding materials or different clinker qualities seem more auspicious
- Break-through technologies concerning new binding materials seem likely
- Overall ecological efficiency is decreased
- Potential of traditional methods like clinker substitution or design optimizations are not completely exploited
- Potential of re-carbonation and recycling post use concrete have not been adequately mapped
- Firing biomass and alternative fuels still has potential

In conclusion the cement industry shares similar constraints towards CCS such as the energy sector or other industries. The survey results particularly demonstrated the need for a clear legal framework to convince companies to believe in this kind of technology, although R&D is seen as the essential key to make the technology available. The uncertainties of the CCS technologies are the main constraint, where only a few companies would be willing to contribute the necessary pilot and demonstration plants. This identifies the need for suitable funding systems and cross-sectoral cooperation. The knowledge gained should then be transferred globally. Smaller and medium sized companies, which are not participants in a consortium, could not afford to handle the high risk on their own, and so they focus on the development of low carbon clinker and alternative fuel use as alternatives for CO_2 reduction. Furthermore, the interest in converting the captured CO_2 by mineralization or reuse it in other products instead of storing it has been highlighted by the respondents as worthy of further investigation.

3 State-of-the-art practice towards CO_2 reduction

This section examines the main four conventional CO_2 reduction measures [HEN-99], which are in the focus of the current cement industry activities:

1. Improve energy efficiency
2. Application of alternative fuels
3. Application of alternative raw materials
4. Clinker substitution in the cement

In order to evaluate the benefit of such measures - especially concerning the CO_2 reduction potential - a reference case is defined which presents the technology aligned to BAT standard. The key assumptions as well as the data of the reference plants are summarized in section 1.3. All calculations and assumptions are based on this reference case unless otherwise specified. Cost data relate to Central European prices and will need to be adapted for other regions in the world, like China, India or Latin America, where the cost structures are very different to Europe.

3.1 State-of-the-art practice

The evaluation of the state-of-the-art practice is based on the CSI/ECRA Technology Papers [CSI-09]. This report identified, described and evaluated technologies which may contribute to increase energy efficiency and to reduce greenhouse gas emissions from global cement production today as well as in the medium and long-term future. The resulting roadmap for the cement industry identified major barriers, opportunities, and policy measures for policy makers, industry and financial partners aiming at an acceleration of research and development of technologies. The reference was based on technical data from CSI’s GNR (Get the Numbers Right) project, in which data from 800 cement installations worldwide have been collected. Since the preparation of the Technology Papers the development of the clinker production technology has not achieved a break-through level, which makes the long and medium term data still valid. Some values have been updated and /or adapted to the different parameters of the chosen reference plant in this study. Moreover the list of measures was extended by adding some newer technologies.

Cost data are related to the reference case and therefore are based on Central European prices. For a sensitivity analysis the costs data are adapted for other regions in the world, like China, India or Middle East. Depreciation, interest and inflation are not included in the cost estimation. Moreover, the costs were adapted to the described reference plant and need to be assessed on the basis of individual plants and cement types when considering specific implementation.

3.1.1 Increase of energy efficiency

Just 63% of the world’s cement production is delivered by facilities which are equipped with precalciner technology and that could be described as state of the art practice. While a large number of cement plants with up-to-date technologies have been built in the last two decades, mainly in emerging countries, there is still a significant number of shaft, wet and semi-dry kilns as well as less efficient grinding equipment in operation worldwide. Therefore, technical optimization of production processes offers a certain but limited improvement potential with respect to the energy demand.

Based on GNR data (2010 data), the thermal energy demand (as a worldwide weighted average) for cement clinker manufacturing was 3,580 MJ/t clinker and the worldwide average electric energy demand for cement manufacturing was 108 kWh/t cement. In total 87% of the total energy input is accounted for by thermal energy input and 13% by electrical power input. According to [CSI-09] the specific energy demand for clinker burning can be reduced to a level of 3,300 to 3,400 MJ/t clinker in 2030 and to 3,200 to 3,300 MJ/t clinker in 2050. It has to be recognized, that the specific plant’s thermal energy demand relies on certain criteria like raw material and fuel properties, production capacity, degree of waste heat recovery or kiln operation. “Break-through technologies which could lead to a significantly higher thermal efficiency are not in sight. Only huge retrofits like changing from wet to dry process allow a significant step in increasing energy efficiency, as wet processes require a thermal energy input up to 5,500 MJ/t clinker. However the potential is limited as only a small fraction of the worldwide clinker volume is produced in wet processes (3%) and semi-wet process (2%) [GNR-10]. For this kind of retrofit a similar level of investment as for new kilns is required. Therefore, they will only be carried out if the market situation is very promising.”[CSI-09]

In the case of the electrical efficiency in grinding processes the potential of a significant increase caused by breakthrough technologies is not in sight either. Comminution under high pressure in a compacted bed of material is still the most efficient industrial grinding method compared to other comminution modes. Vertical roller mills and high pressure grinding rollers can decrease the specific power consumption, but require a high investment. Another limiting factor for the electrical energy demand of grinding systems is e.g. the intended cement quality/product portfolio. Moreover the intensification of environmental standards beyond the values shown in **Table 1-4** may require secondary abatement techniques, which require additional electrical energy.

From today's perspective, a fundamental change in the actual cement production technologies causing a significant reduction in the specific energy consumption is unlikely [CSI-09]. All principle currently available measures to increase the overall efficiency and achieve a certain CO_2 reduction have been listed in the following:

- Change from long kilns to preheater / precalciner kilns

  The objective here is to decommission production plants with high energy demand (long wet and semi-dry kilns) and replace them with energy efficient preheater / precalciner kilns. Retrofitting a long kiln with preheater / precalciner aggregates allows a higher throughout or a cut of the kiln due to the improved utilization of energy in preheater and calcination sections. This results in lower radiation losses as secondary effect. In case of wet kilns the energy reduction potential is even higher due to enhanced usage of heat for preheating the material but this would involve the full reconstruction of the existing plant. This type of change usually does not pay off by the decreased energy demand alone.

- Preheater modification (e.g. cyclones with lower pressure drop)

  By replacing preheater cyclones by cyclones with lower pressure drop, the needed demand of electrical energy for the main exhaust gas fan system (ID fan) can be reduced. However the suitability of the foundations and the suitability for retrofitting the preheater tower must be considered for the rebuilding to be economically reasonable.

- Efficient clinker cooler technology

  Modern grate clinker coolers achieve high cooling efficiencies while simultaneously using relatively low amounts of cooling air. The thermal demand of the kiln plant is therefore lower than that of kiln plants with rotary or planetary cooler types. As grate coolers allow higher production capacity an economical viable replacement is often linked to a change to precalciner technology, which can be provided with additional tertiary air for combustion purposes. The costs can vary widely due to the site specific conditions (new exhaust air fan and cooler filter, foundations and other construction cost, shortening of the kiln). The optimization of clinker coolers (e.g. replacement of cooler plates, installation of a fixed grate section at the cooler inlet) is also an opportunity for some existing kilns, but efficiency improvement potentials are smaller.

- Waste heat recovery (WHR)

  Usually, most of the excessive heat of the clinker burning process is used for drying the raw material, coal/petcoke or blast furnace slag during the grinding processes. Remaining heat (e.g. kiln or clinker cooler exhaust air) can be used for steam production and/or for generating electrical power. Feeding the local heat network makes sense only if industrial consumers or district heating exist in the neighbourhood of the cement plant. Power generation requires a boiler/turbine system, which can be based on a steam process, the ORC (Organic Rankine Cycle) process or the KALINA process. The generated electrical power can cover up to one third of the electrical power demand of a regular cement production facility. However, economic feasibility of WHR mainly depends on local power prices and the reliability of power supply from the national (or regional) power grid. Although, making the kiln process more efficient (by adding e.g. precalciner or cyclone stages) decreases the available waste heat which limits the benefit of a waste heat recovery system.

- Additional preheater cyclone stage(s)

  If the moisture contents of the raw materials are low enough, an additional cyclone stage can be added to an existing preheater tower. By this measure the thermal efficiency of the clinker burning process will be improved. On the other hand the power demand of the fan may be increased due to the higher pressure drop of an additional cyclone stage. Furthermore, the construction of the tower needs to be able to carry the higher load.

- Oxygen enrichment technology

  The use of oxygen enriched combustion air in the clinker burning process allows an increase of production capacity and plant availability, or an enhanced substitution of fossil fuels by often lower calorific (alternative) fuels. Experience of using this technology to increase production capacity has already been gained in the USA in the 1920s. Current research is more focussing on the impact on the burning of alternative fuels. The reduction of inert nitrogen gas flow, which is usually heated up to a maximum of 2,000°C, results in reduced fuel energy demand or setting gas flow capacities free for raising production capacity. This technique requires large amounts of oxygen resulting in an oxygen content in the oxidiser gas (secondary air) of more than 30%. The production of oxygen on-site by air separation requires electric power; approximately 220 kWh/t oxygen. The carbon dioxide intensity for oxygen separation amounts to approximately 125 kg CO_2/t O_2.

- Upgrade plant automation/control package

  With a modern plant control system fluctuations of the production process can be reduced so e.g. unnecessary fuel and power demand caused by unstable process conditions and operational stops can be decreased. Thus parameters like air and mass flow and temperature distribution can be tightly controlled for example automating the weighing and blending processes. Although the typical payback period of 2 years is quite low, the reduction potential strongly depends on the technical equipment, the status of the plant, the availability of the plant and experience of operating staff.

- Increase of the kiln capacity

  By increasing the kiln capacity the specific energy demand for the produced clinker will be reduced, as e.g. specific heat wall losses are decreased. The comparison in **Table 3-1** is made for replacing a 3,000 t/d plant by a green-field 6,000 t/d plant. Importantly, this measure is related to huge investments and is only reasonable in growing markets which require additional production capacity. Local specification like available raw materials might also limit the increase of capacity. Other than the full replacing of the kiln, limited production increases could also be achieved by minor constructive changes (e.g. adding a precalciner) or changed operational modes (e.g. oxygen enrichment).

- Cement grinding with vertical roller mills (VRM) and roller presses (HPGR)

  By the implementation of these grinding units for the raw meal and cement grinding processes the specific energy demand can be reduced significantly as the energy consumption is lower than using a common ball mill. Saving potentials in Europe are limited by the quality requirements of the final product. While high degrees of fineness can be achieved, the resulting particle distribution of cement is steeper than non-ball mill technologies. The particle size distribution influences the cement performance. In other regions of the world, especially in Asia, a huge number of VRM for cement finish grinding have already been installed, as the demand on the product differs from the European Standard. The cement quality, the specific system layout and installed auxiliary equipment might also limit the economic benefit of the mill change. To match the European quality requirements, a HPGR would still need a finish treatment in a ball mill. Moreover although the advanced grinding systems achieve a higher efficiency, process availability may be lower compared to e.g. the less efficient ball mills.

- High efficiency separators

  In a closed mill circuit the material is steadily circulated until the required fineness is reached. The higher the efficiency of the separator the less material is unnecessarily recirculated, so the specific energy demand will be reduced. The operational parameters of the particular mill have to be adjusted to ensure process reliability and to use the separators to full capacity. This is very often restricted by the still limited knowledge of the comminution mechanisms.

- Optimization of operating parameters of ball mills

  With optimized ball mill parameters (load level, revolution speed, ball charge, lining design and the adjustments of the separator) the production process is more efficient, so the specific energy demand can be reduced without additional capital costs. The main obstacles are the complex interdependencies between the mentioned parameters and the limited understanding of the processes inside the grinding chamber. Furthermore, the necessity of grinding different cement types in the same mill requires compromises.

- Variable speed drives

  Every cement plant is operating several hundred motors of which about half are fixed speed models related to the total drive capacity. Because large variations in load occur in cement plants, motor systems are often operated only at partial load. By the use of variable speed drives this throttling can be decreased, so the engine is consuming just the needed amount of energy for the respective process. The energy efficiency, the process controllability and the availability are enhanced as well as motor noise is decreased. However several larger drives, e.g. those of ball mills or crushers, are usually operated at constant speed. As these drives are the main consumers of electrical power and other drives (e.g. of the ID-fan) are usually already equipped with converters, the potential to decrease the electrical energy demand is seriously limited.

In addition to these state-of-the-art practices, new technologies for increasing energy efficiency, which have been suggested but still need to be proven in operation, are listed in the following:

- Fluidized bed advanced cement kiln system

  “Since the late 1990´s a Japanese company has been developing a completely new kiln type based on fluidized bed technology (FBT). In 1989 the first trials were carried out with a pilot plant of 20 tpd and in 1996 with a pilot plant of 200 tpd. At present, a kiln with a clinker capacity of more than 1,000 tpd is being erected in China but it is not yet in operation. Information which has been published from the 200 tpd plant has been used to estimate the CO_2 reduction potential of this technology. On the other hand, it has to be stressed that this technology is not yet available for the cement industry and probably it will hardly be possible to scale up the experiences to a 5,000 or 6,000 tpd clinker capacity.” [CSI 09] Since 2009 no more information has been made available about further developments of fluidized bed technology.

- Advanced grinding technology

  With the development of new grinding systems of higher efficiency the high power demand for the comminution process can be reduced. “Modifications of conventional mills filled with grinding media are on the one hand stirred media mills and on the other hand eccentric vibration mills. These feature a slight increase in energy efficiency but are predominantly limited to wet grinding. Furthermore, the wear of stirring devices and the increased complexity of the gear have to be taken into account. Beyond that, there is a variety of grinding technologies that are still at the stage of development. Considering the problems connected to the durability of wear and tear elements, contact-free grinding systems seem to be promising. Examples are ultrasonic-comminution or plasma comminution. A completely different approach is followed by low temperature comminution. In summary it is perceptible that there is need for much further development of alternative grinding methods. Yet the definitive next generation grinding technology cannot be outlined for different reasons. In the medium term the enhancement of (high pressure) comminution by compression constitutes the only promising approach. Above all, detailed understanding of the breakage processes of materials is required. Only on the basis of such fundamental research efforts is an effective optimization or redesigning of existent grinding technology possible" [CSI-09]. No new information about breakthrough grinding technologies has come up since 2009.

The impacts on energy efficiency, CO_2 reduction potential and costs of the measures described above are listed in **Table 3-1** to **Table 3-3**. The upper parts of the tables contain modifications at the kiln plant and the lower parts modifications at the grinding plant. In general the described methods to increase the energy efficiency rely on the modernization of certain plant components, for which reason the effectiveness of these methods is depending on the specific technology standard of the plant. Some of even preclude each other, e.g. the implementation of waste heat recovery systems and the addition of preheater stages.

Table 3-1 Impact on energy demand based on [CSI-09]

Method	**Thermal energy** **MJ/t clinker**	**Electrical energy** **kWh/t clinker**
Change from long kilns to preheater / precalciner kilns	decrease of 900 – 2,800	decrease of 0 - 5
Preheater modification	0.0	decrease of 0.6 – 1.5
Efficient clinker cooler technology	decrease of 100 - 300	increase of 1 - 6
Waste heat recovery (for power generation)	0.0	decrease of 8 - 22
Additional preheater cyclone stage(s)	decrease of 80 - 100	0.0
Oxygen enrichment technology	decrease of 100 - 200	increase of ~ 39
Upgrade plant automation/control package	decrease of 50 - 200	decrease of 0 - 1
Increase of the kiln capacity (2 Mt/y capacity)	decrease of 150 - 200	decrease of 2 - 4
Fluidized bed advanced cement kiln system	decrease up to 300	increase up to 9
Method	**Thermal energy** **MJ/t cement**	**Electrical energy** **kWh/t cement**
Cement grinding with vertical roller mills and roller presses	0.0	decrease of 12 - 16
High efficiency separators	0.0	decrease of 4
Optimization of operating parameters of ball mills	0.0	decrease of 0 - 2
Variable speed drives	0.0	decrease of 3 - 9
Advanced grinding technology	n/a	n/a

Table 3-2 CO_2 reduction potential [CSI-09]

Method	**direct CO_2 reduction** **kg CO_2/t clinker**	**indirect CO_2 reduction** **kg CO_2/t clinker**
Change from long kilns to preheater / precalciner kilns	decrease of 80 – 250	decrease of 0 - 3.5
Preheater modification	0.0	decrease of 0 -1
Efficient clinker cooler technology	decrease of 9 – 28	increase of 1 – 3
Waste heat recovery	0.0	decrease of 4 - 15
Additional preheater cyclone stage(s)	decrease of 6 – 8	0.0
Oxygen enrichment technology	decrease up to 170	increase of 15 – 25
Upgrade plant automation/control package	decrease of 4 – 18	decrease of 0 – 0.7
Increase of the kiln capacity (2 Mt/y capacity)	decrease of 15- 20	decrease of 1 – 3
Fluidized bed advanced cement kiln system	decrease up to 27	increase of 4 – 6
Method	**direct CO_2 reduction** **kg CO_2/t cement**	**indirect CO_2 reduction** **kg CO_2/t cement**
Cement grinding with vertical roller mills and roller presses	0.0	decrease of 7 – 11
High efficiency separators	0.0	decrease of 2 - 3
Optimization of operating parameters of ball mills	0.0	decrease of 1 - 2
Variable speed drives	0.0	decrease of 1 - 5
Advanced grinding technology	n/a	n/a

Table 3-3 Investment and operating costs based on [CSI-09] for 1 Mt/y clinker capacity

Method	Investment costs M €	Operating costs €/t clinker
Change from long kilns to preheater / precalciner kilns	35 - 50	2.85 – 9.2 decrease
Preheater modification	6 – 7	0.05 – 0.08 decrease
Efficient clinker cooler technology	1 – 15	0 – 0.5 decrease
Waste heat recovery (for power generation)	11 – 20	0.3 – 1.2 decrease
Additional preheater cyclone stage(s)	2.5 – 4.5	0.23 – 0.26 decrease
Oxygen enrichment technology	0.05 – 0.1	0.5 – 2.3 increase
Upgrade plant automation/control package	0.15 – 0.2	0.22 – 0.74 decrease
Increase of the kiln capacity (2 Mt/y capacity)	240	1.4 – 1.7 decrease
Fluidized bed advanced cement kiln system	not available	up to 0.3 decrease
Method	**Investment costs M €**	**Operating costs €/t cement**
Cement grinding with vertical roller mills and roller presses	22	0.25 – 0.85 decrease
High efficiency separators	1.8	0.28 decrease
Optimization of operating parameters of ball mills	0.01	0 – 0.15 decrease
Variable speed drives	0.18 – 0.25 (1,000 kWh)	0.3 – 0.7 decrease
Advanced grinding technology	n/a	n/a

3.1.2 Application of alternative fuels

In cement production the major portion of thermal energy is required for the burning of the cement clinker. In 2010 in the cement industry, fossil fuels accounted for 88 % of the total fuel input worldwide (recorded amongst CSI members). About 3% of the total fuel has been supplied as biomass and a further 9% of the fuel has been derived from different fossil-based waste streams. Hard coal, lignite, petcoke, gas and oil are the most common fuels in the cement industry while the share of alternatives is increasing in several regions of the world. Alternative fuels are derived from mainly fossil waste streams like waste oil, tyres, plastics, solvents, mixed industrial waste or other fossil-based wastes. Alternative fuels may also contain biomass fractions whilst some waste derived biomass fuels are considered to be pure biomass for example animal meal, sewage sludge, waste wood and grain rejects. With respect to geographical location, the use of alternative fuels in the cement industry is quite unevenly distributed. Plants which use alternative fuels usually have substitution rates above 30% while about half of the plants do not use alternative fuels at all [GNR-10].

An increasing replacement of fossil fuels by alternative fuels is one of the key measures for reducing carbon dioxide emissions from combustion in cement clinker manufacturing. The CO_2 reduction potential of alternative fuels results mainly from fuels exhibiting a biomass fraction of which the carbon dioxide emission factor is accounted as zero, and from lower specific carbon dioxide emission factors per heat equivalent in comparison to fossil fuels (compare **Table 1-3**). Nevertheless the reduction potential of fuel switching is limited to the CO_2 released from combustion and does not influence the 60% of the CO_2 emissions arising from feed material itself. Furthermore, the use of alternative fuels both saves natural resources and reduces carbon dioxide emissions arising outside the cement plant if residues and wastes are utilized as alternative fuels in the plant instead of land filling or incinerating them in separate installations. The CO_2 reduction potential is shown in **Table 3-5**.

In principal, cement kiln conventional fossil fuels can be substituted up to 100% by alternative fuels. The worldwide substitution of fossil fuels is quite low at 12% but in Europe the substitution has reached 30% (in 2010). Until 2013, few plants in the European region had already successfully deployed 90% or more alternative fuels in normal operation.

Nevertheless, there are certain technical limitations like the calorific value, the moisture content, particle size and shape, and the content of minor compounds, trace elements or chlorine. The calorific value of most organic material is comparatively low (10 to 20 GJ/t). For the rotary kiln firing system an average calorific value of at least 20 GJ/t is desirable, meaning that high calorific alternative fuels are the most attractive. In the precalciner, in which up to 60% of the total fuel input is used, the lower process temperature allows also the use of low calorific fuels. Therefore, precalciner kilns are able to utilize about 60% of low calorific fuels.

A lower calorific value and high-chlorine content of alternative fuels requires a system called gas bypass which provides an extraction of a certain amount of gas at the kiln inlet, where the highest concentration of chlorine in the gas phase occurs. After cooling down this gas the chlorine condenses on the surface of the meal particles and is separated in the filter. This extraction of hot gases may lead to decreased energy efficiency by the use of alternative fuels. Furthermore, the use of waste fuels at higher substitution ratios may limit or reduce clinker capacity of the kiln system due to the higher specific exhaust gas volume, which influences the meal/gas ratio and may cause dysfunction of the preheater. The calculated influence on the thermal energy demand is shown in **Table 3-4**.

Alternative fuels differ in their combustion characteristics from fossil-based fuels like coal or pet-coke. Many waste streams require a larger processing effort before they can be used as a kiln fuel. For this purpose an adaption of the burner may become necessary and supplying infrastructure or pre-treatment technology (e.g. drying/grinding) might need to be added, which requires a certain investment for handling and storage. On the other hand the usually lower prices of alternative fuels contribute to lower operating costs. It is expected that the lower CO_2 emissions related to energy content of many alternative fuels as well as a reduced availability of high quality alternative fuels will increase their market price in the future. Thus the impact on future operating costs is not predictable. A cost estimation based on the current development is given in **Table 3-6**.

In order to improve the use of alternative fuels different technologies can be used or are subject to current research. In addition these technologies can smooth the kiln operation, which could be affected by heterogeneity of the alternative fuel composition. These measures therefore lower the specific thermal energy demand of the process in the course of time and increase plant availability and productivity. Technologies subject to current research include:

- Gasification of alternative fuels

  Gasification of low-calorific alternative fuels (high moisture, coarsely sized) instead of pretreating and feeding the fuels directly to the calciner could increase operational stability due to homogeneity of the energy source. By improving the stability of the system this energy delivery technique can slightly contribute to reduction of costs and CO_2 emissions, but this is difficult to quantify. Fuels can be gasified in fluidized or fixed bed chambers or suspension flow processes, so that a low-calorific lean gas with high carbon monoxide concentrations is produced and then supplied to the calciner firing system. Precombustion chambers are already used at certain calciner designs.

  Moreover within an EU funded research project the application of a plasma burner for gasification of biomass is currently being investigated [VDZ-13].

- Oxygen enrichment to enhance combustion of alternative fuels

  Oxygen enrichment of the combustion air the oxygen content can increase the combustion air beyond the normal content in air of 21% by volume. Oxygen could either be fed to the primary air directly at the burner or to the combustion air to increase the overall oxygen level. The overall intention of oxygen enrichment is raising production output and saving in fuel consumption (see chapter 3.1.1). The feeding of oxygen to the primary air heightens the local oxygen level in the flame core intensively (up to 40%). It allows for targeted fuel replacement – especially the replacement of high-grade fuels by fuels with low calorific value, poor ignition or combustion properties. Therefore low calorific fuels may become more useful in the main burner. The calculation in **Table 3-4** is based on an increase of alternative fuels by 10%.

Table 3-4 Impact on thermal and electrical energy demand due to the application of alternative fuels based on [CSI-09]

Method	**thermal energy** **MJ/t clinker**	**electric energy** **kWh/t clinker**
Fossil fuel replacement	increase of 0 to 300	increase of 0 to 3
Oxygen enrichment of primary air (up to 40 vol.%)	not relevant	direct: not relevant indirect: up to 1.5

Table 3-5 CO_2 reduction potential for application of alternative fuels based on [CSI-09]

Method	**direct CO_2** **kg CO_2 / t clinker**	**indirect CO_2** **kg CO_2 / t clinker**
Fossil fuel replacement	decrease of 80 to 200	increase of 0 to 2
Oxygen enrichment of primary air (up to 40 vol.%)	decrease of 80 to 200	increase of up to 0.7

Table 3-6 Investment and operating costs for the application of alternative fuels based on [CSI-09] for 1 Mt/y clinker capacity

Method	**Investment costs** **M €**	**Operating costs** **€/t clinker**
Fossil fuel replacement	3.5 - 10	1 to 8 decrease
Oxygen enrichment of primary air (up to 40 vol.%)	0.05	increase of up to 0.5 to decrease of up to 7

3.1.3 Application of alternative raw materials

Calcium oxide is one of the major compounds of cement. The source material for the calcium oxide is usually calcium carbonate which is the main constituent of limestone, marl and chalk. Further constituents are silicon dioxide, aluminium oxide and iron oxide, which are fed to the process as iron ore, bauxite or sand and which can be found in fuel ashes. The most energy consuming process is the decarbonation of the limestone, which release carbon dioxide. The utilisation of alternative calcium containing raw materials which are already decarbonated offers an option to reduce CO_2 emissions. These are reduced by both, process-related CO_2 emissions from the decarbonation of the raw materials as well as CO_2 emissions from the related fuel energy input for the decarbonation.

Blast furnace slag, lignite ash, coal ash, concrete crusher sand, aerated concrete meal, corresponding fractions from demolition wastes or lime residues from the sugar industry are examples for such decarbonated alternative raw materials. The utilisation of alternative materials is in general limited by their overall composition as they need to be combined with locally available raw materials to formulate the composition of cement clinker. The excess amount of silica, alumina, magnesia or sulphur may therefore hinder a large-scale utilisation of alternative decarbonated raw materials, the content of Volatile Organic Compounds (VOC) or trace elements and variable compositions may cause a further restriction in some cases. Furthermore the availability of such decarbonated raw materials is limited. The local situation may allow no or only a very limited use of alternative decarbonated raw materials. The use of granulated blast furnace slag (GGBS) may be realistic up to an amount of 15% of the raw meal in a few cases. The utilisation of an even higher amount is in principle possible but seems to be unrealistic in any case due to the decreasing availability of GGBS and its rising costs. Moreover, additional effort for the grinding of these materials is needed because of their structure requiring a higher electrical energy demand. Further preparation steps, e.g., in case of concrete crusher sand, may improve the quality of the material but does also enlarge the costs and the environmental efforts for the material supply.

A better economic and environmental use of most of these substitutes such as blast furnace slag or fly ash is evident in clinker substitution within cement instead of a substitution of raw materials. Although these raw material substitutes reduce the fuel and material CO_2 emissions by energy savings and lower CO_2 content in the feed material itself, the utilisation in cement leads to improved saving potential and higher product quality enhancement (see section 3.1.4) [CSI-09].

The substitution of conventional raw materials by concrete crusher sand in the cement clinker production leads to a reduction of energy demand and CO_2 emissions in the clinker burning process due to the use of not yet carbonated hardened cement paste in concrete crusher sand. Concrete crusher sand is characterised by high amounts of silicon dioxide and calcium oxide. The sand may replace 3% of the conventional raw materials. At this substitution ratio a very small carbon dioxide reduction and energy saving of less than 1% may be achieved.

A recent study [Red-11] determined the potentials and limitations of the use of fibre cement materials in cement clinker manufacturing. Fibre cement wastes originate from their production or demolition and consist mainly of Portland cement and a mix of carbonaceous fillers and silica fume. These materials can be used as a substitute material for the production of cement clinker. Due to organic components forming VOC emissions the fibre wastes cannot be fed to the top of the preheater in large amounts. Feeding fibres to the kiln inlet, the VOCs are decomposed, but large amounts of cold materials fed directly to the kiln lower the energy efficiency. Rotary kiln lines with calciner technology can deploy up to 20% fibre cement material in the raw material mixture. Process conditions, clinker quality and rotary kiln design limit their use. The fibre cement material is mainly calcined material. The use of fibre cement products therefore reduces the release of carbon dioxide from the kiln feed which in turn decreases carbon dioxide emissions from the raw materials. As no energy is required for the calcination of the already calcined content of the fibre cement material, the reaction energy of the kiln feed is lowered which results in less carbon dioxide emissions from fuels. At a substitution ratio of 20% a carbon dioxide saving of around 10% could be achieved. As less energy for the calcination is required the total energy consumption for the cement clinker manufacturing is lowered of by around 300 kJ/kg clinker (see **Table 3-7**). Due to the low availability of fibre cement waste materials today, only very few plants use them currently as raw material substitute.

The utilisation of alternative calcium containing raw materials which are already decarbonated reduces process-related CO_2 emissions from the decarbonation of the raw materials and CO_2 emissions from the related fuel energy input saving (compare **Table 3-9**) [HAU-09].

Table 3-7 Impact on thermal and electrical energy demand due to the application of alternative raw materials [RED-11, CSI-09]

Method	thermal energy MJ/t clinker	electric energy kWh/t clinker
15% replacement by granulated blast furnace slag	decrease of 100 to 400	increase of 0 to 3
20% replacement by fibre cement material	decrease of approx. 300	increase of 0 to 3

Table 3-8 CO_2 reduction potential for application of alternative raw materials [RED-11, CSI-09]

Method	**direct CO_2** **kg CO_2 / t clinker**	**indirect CO_2** **kg CO_2 / t clinker**
15% replacement by granulated blast furnace slag	decrease of 0 to 115	increase of 0 to 2
20% replacement by fibre cement material	decrease of approx. 90	increase of 0 to 2

These figures have to be regarded as possible site-specific reduction potentials but not as a range for the overall reduction potential for the cement industry. High reduction potentials can probably only be achieved at very few sites with specific alternative raw materials.

Table 3-9 Investment and operating costs for the application of alternative raw materials [CSI-09] for 1 Mt/y clinker capacity

Method	**Investment costs** **M €**	**Operating costs** **€/t clinker**
replacement by decarbonated material	< 6	increase 1 to 4.2

Investment costs include the costs for storage and handling of the additional raw material: Operating costs include the costs for the alternative raw material, fuel saving, saving of replaced raw materials and additional power (**Table 3-9**). Additional costs may occur by the impact on the raw mill wear which have not been taken into account in the cost estimation.

3.1.4 Clinker substitution

Cements that contain other constituents in replacement of clinker exhibit a lower clinker-to-cement-ratio than Portland cement. Consequently these cements require less energy demand for the clinker burning as well as less process CO_2 emissions due to the decarbonation of the limestone per tonne of produced cement. The material related CO_2 footprint of the substitution components is lower than that of clinker, but is not included in the following calculation as it is already accounted for other processes. Based on a global clinker-to-cement ratio of 76% (as weighted average) and a worldwide cement production of about 3,300 Mt this is equivalent to the use of about 800 M t of clinker substitutes. Moreover the other cement constituents show hydraulic and/or pozzolanic reactivity or filler properties and contribute positively to the cement performance.

The CO_2 reduction potential is strongly dependent on the substitutes’ influence on cement properties and the availability of the substitutes for clinker replacement. These aspects are listed in the following for each material:

- Ground granulated blast furnace slag (GGBS)

  Molten iron slag is a by-product of the iron production process and can be quenched in water or steam. The glassy, granular product is named granulated blast furnace slag

(GBFS). GBFS is latently hydraulic, i.e. its hydraulicity has to be activated e.g. by calcium hydroxide that is formed by the hydration of clinker. Currently an estimated 200 M t/a GBFS are produced worldwide. Grinding granulated blastfurnace slag into GGBS makes it useful as a clinker replacement.

- Fly ash (FA)

  Fly ash is obtained by precipitation from the flue gases of coal-fired furnaces. FA may be siliceous or calcareous in nature and has pozzolanic properties (calcareous FA may have little hydraulic properties besides the pozzolanic properties). The actual worldwide fly ash production is about 900 Mt/a which is not all suitable for cement or concrete production. With respect to the CO_2 discussion the future number and capacity of coal fired power plants is hard to predict.

- Pozzolana

  Pozzolana are usually natural pozzolana (materials of volcanic origin or sedimentary rocks) or natural calcined pozzolana (materials of volcanic origin, clays, shales or sedimentary rocks, activated by thermal treatment). Other pozzolanic materials like rice husk ash can also have particularly local relevance. Pozzolana contain siliceous or silico-aluminous phases which can react in cement paste and contribute to strength-development. In 2003 about 30 Mt of natural pozzolana were available worldwide, but only about 50% were used in cement and concrete industries. The amount of natural pozzolana depends on the local geological conditions, and it can be stated that they are not widely available for cement production.

- Limestone

  The intergrinding of limestone as a minor or main constituent is an efficient method to reduce the clinker/cement ratio of cement. However, limestone does not contribute to strength formation of the cement paste. If limestone-containing cements are adjusted to give the same strength like Ordinary Portland cement (OPC) they have to be ground more finely. Furthermore, the resistance to acids and sulfates and the freeze-thaw-resistance of limestone-containing cements may be impaired. As an advantage, limestone often leads to a better workability of the concrete. Limestone is available for most cement plants, and the worldwide availability will not be a limit within the next few hundred years.

The use of the described main cement constituents (GBFS, FA, pozzolana, limestone) is a suitable way to reduce the clinker content and the CO_2 emission of cement production. Their potential primarily depends on the regional and global availability and on the quality of the respective constituent and of the clinker. Assuming that the availability of slag, fly ash and pozzolana will increase in the same rate as cement consumption (no detailed information is available confirming this hypothesis) the potential for a further reduction of the clinker-to-cement-ratio with these materials is significant, but limited. Because of this limited availability other materials like calcined clays, alternative pozzolanic or latent hydraulic materials that could be derived from waste should be taken into account.

The application regulations for cement are based on the extensive practical experience in the various countries where the cement is used successfully with their respective concrete compositions, concrete cover and curing under the corresponding climatic conditions in accordance with the building traditions and safety requirements. Therefore in some regions of Europe further increase of clinker substitution (e.g. CEM IV and CEM V) is not permitted or restricted due to the respective requirements which are specific in those countries. However, current research showed that different combinations of substitute materials are able to match quality requirements.

In addition to the substitution of clinker in the cement, other cement types are offer advantages which could improve the energy demand of the clinker burning process by their raw material chemistry.

- Belite cement

  Ordinary Portland Cement (OPC) clinker typically contains 40 to 80% by mass alite ($C_3S = Ca_3SiO_5$). In contrast, so-called belite clinker contains no or only small amounts of alite but up to 90% by mass belite ($C_2S = Ca_2SiO_4$). This type of clinker can be burnt like OPC clinker but with lower amounts of calcium (lime saturation factor LSF down to 80) and at lower temperatures around 1,350 °C. In principle, fuel energy and CO_2 emissions can be saved due to the reduction of limestone content in the raw material and the reduced burning temperature. However, contrary to some general opinion, the associated saving in fuel energy is less than 10% due to the less efficient heat recovery in the cooler [WOL-05]. This has to be balanced against the fact that belite clinker is very hard to grind and therefore requires more grinding energy.

- Calciumsulfoaluminate cement (CSA)

  Excess sulphate addition to the raw meal leads to the formation of sulphoaluminate clinker containing yeelimite ($C_4A_3s = Ca_4Al_6SO_{16}$) as another hydraulic phase in addition to belite. By addition of further aluminium oxide other calcium aluminates like CA ($CaAl_2O_4$) and mayenite ($C_{12}A_7 = Ca_{12}Al_{14}O_{33}$) these cements show short setting times and enhanced early strengths due to the formation calcium aluminate hydrates during hydration. The reduced lime content and the easier sintering by mineralization result in a decreased heat demand. On the other hand the higher sulphur content in the kiln system causes an increased cycle formation and therefore a higher risk of incrustation formation. Today, the use of sulfoaluminate cements for concrete production mainly limited to China.

The main difference of blended cements or belite cements is the low early strength compared to OPC. The market acceptance of such cements is therefore often limited, furthermore standards and regulations can be a barrier. Product quality and logistics are often other challenges. The use of bauxite and sulphates as raw material makes the CSA-cements expensive. Furthermore, durability is lessened e.g. with respect to carbonation related with increased porosity and strength loss.

The reduction potential for energy (**Table 3-10**) and CO_2 emissions (**Table 3-11**) as well as the cost estimation (**Table 3-12**) are based on the reference plant data as a starting point (see section 1.3). Therefore, the reduction potential is higher if OPC is replaced by blended cements.

Table 3-10 Impact on thermal and electrical energy demand based on the clinker substitution in cements and lower carbonate clinkers, based on [CSI-09]

Method	**thermal energy** **MJ/t cement**	**electric energy** **kWh/t cement**
Cement with 30-70% blast furnace slag	decrease of 240 - 1,500	no significant influence
Cement with 25-35% fly ash	decrease of 80 - 400	decrease of 2 - 11
Cement with 15-35% pozzolana	decrease of 0 - 400	no significant influence
Cement with 25-35% limestone	decrease of 80 - 400	decrease up to 12
Lower carbonate clinkers	decrease of 150	increase of 20 - 40

Table 3-11 CO_2 reduction potential based on the clinker substitution in cements and lower carbonate clinkers, based on [CSI-09]

Method	**direct CO_2 reduction** **kg CO_2/t cement**	**indirect CO_2 reduction** **kg CO_2/t cement**
Cement with 30-70% blast furnace slag	60 - 380	no indirect CO_2 reduction
Cement with 25-35% fly ash	20 - 100	1 - 8
Cement with 15-35% pozzolana	0 - 100	no indirect CO_2 reduction
Cement with 25-35% limestone	20 - 100	decrease 6 - 8
Lower carbonate clinkers	50	increase of 10 - 30

Table 3-12 Investment and operating costs for the clinker substitution in cements and lower carbonate clinkers, based on [CSI-09] for 1 Mt/y clinker capacity

Method	**Investment costs** **M €**	**Operating costs*** **€/t cement**
Cement with 30-70% blast furnace slag	5 - 10	
Cement with 25-35% fly ash	6 - 9	
Cement with 15-35% pozzolana	6 - 9	
Cement with 25-35% limestone	6 - 9	
Lower carbonate clinkers	6 - 9	

* Operating costs can vary within a high range due to huge number of interdependencies of influencing factors

The named cost values are based on certain boundary conditions as listed below:

- Capital costs are due to extra storage capacity for the clinker substitutes and the cements as well as the technical equipment for handling and drying of the materials.

- For the use of natural calcined pozzolana a calcination step will be necessary, which induces costs for additional fuels and technical equipment.
- Operational cost savings depend on the purchase costs of the clinker substitutes, reduced fuel and power costs for clinker production, increased electricity costs for raw material and cement grinding, reduced handling and mining costs.
- Specific investment costs related to the tonne of produced cement will be lower as the clinker/cement ratio is further decreased.

3.1.5 New cement formulations and high performance concretes

Based on the described methods of clinker substitution in the cement, the cement itself could be reduced in the concrete or even replaced by other new binding materials. The role of new types of cements/binders is still uncertain. The availability of starting materials is not clear and current research shows only limited potential for mass production.

- Concrete with reduced cement contents

  Another theoretical possibility for the reduction of CO_2 in concrete is the use of high performance cements in place of conventional cements. The use of cements of a high strength class (52.5) instead of a cement of a lower strength class (32.5) is conceivable. These classes are mainly defined by the clinker phase composition (depending on raw material composition and operational mode), the properties of substitution materials named above as well as particle size. The question is to what extent the cement content of the concrete could be lowered in this way? It has to be considered that the compressive strength of structural building concretes of usual composition depends only secondarily on the cement strength class and on the cement content. The water to cement ratio is of substantially greater importance in this respect. The cement content itself has a strong influence on the workability and the durability of the concrete. The cement paste component causes a dense microstructure and guarantees the alkalinity of the concrete, which prevents the corrosion of reinforcing steel. For these reasons minimum cement contents are defined in rules and standards for the concrete construction method. The use of high performance cements in order to decrease the cement contents of concrete therefore offers no or only a very limited potential for the reduction of CO_2. A comparison of energy efficiency or an estimation of costs is therefore not reasonable.

- New binding materials

  Besides the approach to reduce the process CO_2 emissions by the reduction of clinker content in the cement or low-carbonate clinker, new binding materials are investigated. But these technologies are still in research or pilot scale. One of these is the so-called Celitement [MOL-12], which is produced on the basis of a lower carbon content in an autoclave process with subsequent reaction grinding. In a pilot plant, capacity rates up to 100 kg/d can be achieved. Due to its research status comprehensive data about the material and the process, e.g. energy demand, are not available. The first field of application is assumed in special construction materials such as tile adhesives, fillers, plasters or mortars. Other approaches like Novacem (based on magnesia binder) or Calera (based on CO_2 mineralization) have been discontinued or no significant progress has been reported during the last years. Other potential new binders are geopolymer cements, which are two-component binders consisting of a reactive solid component and an alkaline activator. During the reaction in alkaline media a three-dimensional inorganic alumosilicate polymer network is built, which is responsible for the relatively high strength of the hardened product. Until now, geopolymers have been produced only for demonstration purposes and have only been used in non-structural applications, e.g. pavings. Suitable materials for a geopolymeric polycondensation are alumosilicates which can be of natural (metakaolin, natural pozzolana) or industrial (fly ashes, granulated blast furnace slags) origin. In any case the availability of these materials is limited. As a consequence, even if technical barriers might be overcome, geopolymers will only be able to be produced in limited quantities.

3.1.6 Summary

All the technologies outlined in this section can contribute to a reduction of combustion and material related CO_2 emission to a greater or lesser degree. However, the calculated potentials could not be simply added, as some of them are counteracting each other. For example, the application of waste heat recovery systems are not reasonable, if other techniques (like adding a cyclone stage) increases the kiln plant’s efficiency and therefore reduces the available waste heat. Moreover some measures, which enhance thermal energy efficiency, include penalties concerning the electrical energy demand and related indirect CO_2 emissions, e.g. the oxygen enrichment increases production capacity but needs power to supply the oxygen or the production of belite cements reduces the heat demand, but requires more effort for grinding.

Nevertheless a simulated “blue map scenario” by IEA showed that 44% of the target CO_2 reduction potential in the cement industry related to the base scenario in 2050 could be achieved by the described conventional methods. This indicates the prospects that these methods have but also the limits of their reduction potential.

According to the given scenario the increase of plant efficiency by retrofitting or replacing existing plant equipment offers a potential to contribute to the target CO_2 reduction requirement in 2050 by 10%. This statement points out, that the today’s potential is already exploited to a great extent. This includes, in particular, the modernisation of equipment in older plants in some regions of the world. Nevertheless, fundamental changes in cement manufacturing technology are unlikely and investment costs are very high.

Utilization of alternative fuels and biomass can reduce anthropogenic CO_2 emissions due to their lower carbon content as well as their biogenic fraction. The overall CO_2 emissions of a cement kiln plant are not necessarily decreased, but via combustion of biomass the CO_2 is available to be bound again in its life cycle by vegetation and is therefore assumed as carbon neutral. However, due to different and partly varying properties, the process-integrated drying as well as the (in many cases) necessity of installing a bypass system the thermal energy demand of the process may rise. Measures like oxygen enrichment and gasification could partly compensate this effect but at the expense of higher electrical energy demand. In general, when alternative fuels are applied, knowledge is required in order to adapt the process to the differing fuel properties. This experience and knowledge exists in some world regions or companies respectively, whereas it is lacking in others. The importance of alternative fuels continues to grow globally due to the positive economic and environmental aspects. Investment costs of this fuel switch originate mainly from storage and handling and in some circumstances from pretreatment. Operating costs are lower due to alternative fuels prices compared to regular fuels like coal. In summary the application of alternative fuels and other fuel switching offer the potential to contribute to the target CO_2 reduction requirement in 2050 by 24% compared to the base case [IEA-09/2].

The application of alternative raw materials can help towards the reduction of the process related, as well as fuel related, CO_2 emissions. When waste materials replace natural raw materials, resources may be preserved and sustainability is improved. Using decarbonated materials CO_2 emissions provide additional benefit, as their CO_2 is already discharged in previous treatments/processes. Limitations are mainly given by the availability and the composition of the alternative materials themselves. Moreover, the raw material mixture has to be corrected in its composition, which is only possible to a certain extent and depends on the natural mineral deposit. Cement plants using marl are therefore limited in the utilization of additional alternative materials as more expensive corrective materials have to be added. In addition to wastes from recycled concrete or fibre cements materials like blast furnace slags or fly ashes can be used as alternative raw materials. Due to their limited availability, it is more reasonable to use them as clinker substitute in the cement because higher reduction potentials could be achieved.

A lower clinker-to-cement-ratio results in less energy demand for the clinker burning as well as less process CO_2 emissions from the decarbonation of the limestone. The most important clinker replacing constituents are fly ash, slag, limestone and pozzolana. It has to be taken into account, that the blended cements that contains these clinker replacement materials may have different or even limited properties compared to Ordinary Portland Cement. The most limiting effect, on the other hand, is the availability of most of these materials. Furthermore, the production of low carbonate clinker exhibits mainly technical challenges.

The approach to reduce the process CO_2 emissions by the reduction of clinker content in the cement or low-carbonate clinker, new binding materials have been investigated, but these technologies are still in research or pilot scale. In which extent these materials like Celitement, Novacem or Calera could replace cement as binder in building materials is not foreseeable today.

4 Research and CCS activities in the cement industry

4.1 Introduction

Carbon Capture and Storage technologies (CCS) imply that CO_2 arising from combustion processes and from process industries are captured and stored away from the atmosphere for a very long period of time. For this purpose CO_2 has to be separated and captured from the process. In this section of the report different categories of capture technologies are discussed, namely: pre-combustion, post-combustion and oxyfuel technology.

Up to now, no results from industrial scale trials at rotary cement kilns using any of the described capture methods are available. Therefore considerations on carbon capture in the cement industry are mainly the product of theoretical studies with limited experimental evaluation. Based on several feasibility studies the first pilot scale projects are planned or have even started operation on the basis of different post-combustion technologies. Further research, development and demonstration is required before capture technologies can be economically applied to the clinker burning process at an industrial scale. However, some capture technologies seem to be more appropriate for the potential application at cement kilns than others:

Pre-combustion technologies are aiming to produce fuels which are more or less carbon-free by a reforming or gasification process (see **Figure 4-1**). Regarding the clinker burning process, a significant disadvantage of pre-combustion CO_2 capture is due to the fact that only the CO_2 from fuel combustion (and not from the calcination of the limestone in the raw material) would be reduced. Thus about 60% of the generated CO_2 emissions would remain unabated. Moreover, the application of pre-combustion technology would entail the most extensive changes to the clinker burning process when compared to the other candidate capture technologies. The shift to hydrogen combustion would be very demanding and would trigger a series of research tasks to adapt the clinker burning process to the new conditions. Based on these difficulties the Pre-combustion technology is the least favourable or can even be excluded as the potential capture technology for the cement industry [ECR-07, ECR-09]. For this reason this technology will not be discussed further in this report.

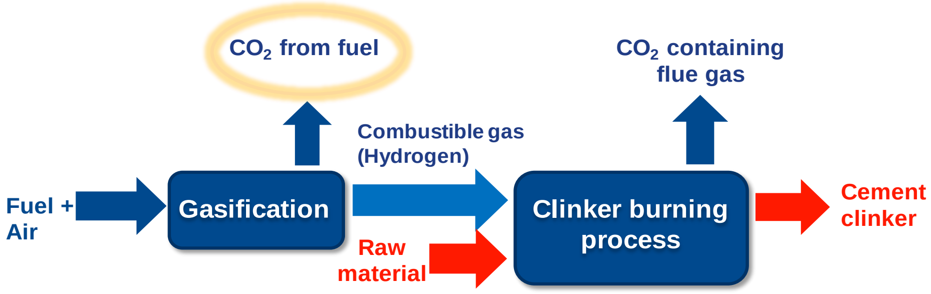

Figure 4-1 Principle of the Pre-combustion technology

Post-combustion capture is an end-of-pipe measure and would not require fundamental changes to the clinker burning process (see **Figure 4-2**). Therefore, this technology would be applicable not only for new kilns, but also for retrofits at existing cement kilns. Both sources of CO_2 - fuel combustion and process CO_2 - are captured when applying post-combustion measures.

Post-combustion technologies rely on the downstream separation of CO_2 using different chemical or physical measures, e.g.

- chemical absorption (amine scrubbing, chilled ammonia)
- membrane technologies
- adsorption technologies
- mineralisation
- calcium looping

The most proven post-combustion technology is chemical absorption because there are operational experiences from several industries and high abatement efficiencies have been reported to be achievable. Although additional investigations and pilot trials have to be carried out in the coming years, this technology is seen as a carbon capture solution for the clinker burning process, which could become available in the short-term [ECR-07, ECR-09]. It is expected that post-combustion capture will be commercially available for the power sector after 2020 [ZEP 2008]. Whereas the technology is viable in the power sector the economic feasibility still needs to be enhanced for commercialisation.

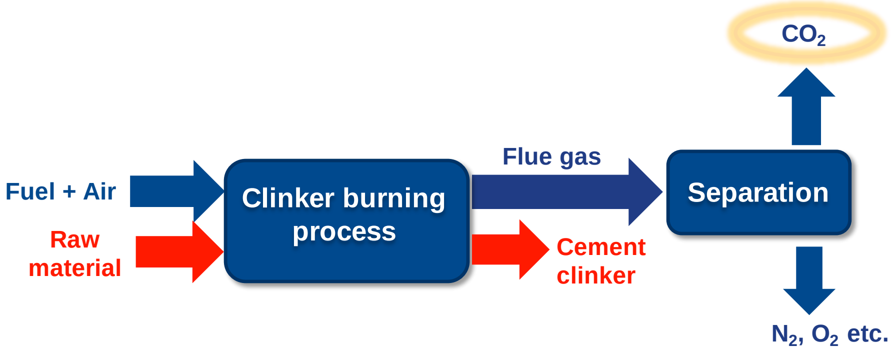

Figure 4-2 Principle of the post-combustion technology

Oxyfuel technology is another method for CO_2 capture at cement kilns. In cement kilns the use of oxygen - provided by an air separation unit (ASU) - instead of air would result in a comparatively pure CO_2 stream, which after purification and compression, could be supplied to a CO_2 transport infrastructure (see **Figure 4-3**). To maintain an appropriate flame temperature, a certain amount of flue gas has to be recirculated. Thus the combustion temperature is controlled by the recirculation rate as an additional process control. This integrated system will have a huge impact on the clinker burning process, mainly an energy shift caused by the different gas properties as well as the ratio between the enthalpy flow of the kiln gas and the energy needed for the preheating of the kiln feed. In an optimised operation this influence and the variable oxygen concentration could even benefit the clinker burning process by increasing its thermal energy efficiency. There are some experiences from cement kilns which were operated with oxygen enrichment (to increase the production capacity or enhance the use of alternative fuels). Furthermore, oxyfuel technology has been investigated at power plants in recent years, so that some of the results obtained may be transferred to cement kilns. Nevertheless there is a need for research activities before the technology can be applied on an industrial-scale. Due to its advantages of improving energy demand compared to other capture methods the oxyfuel technology is seen as a promising method for the long-term perspective [ECR-09].

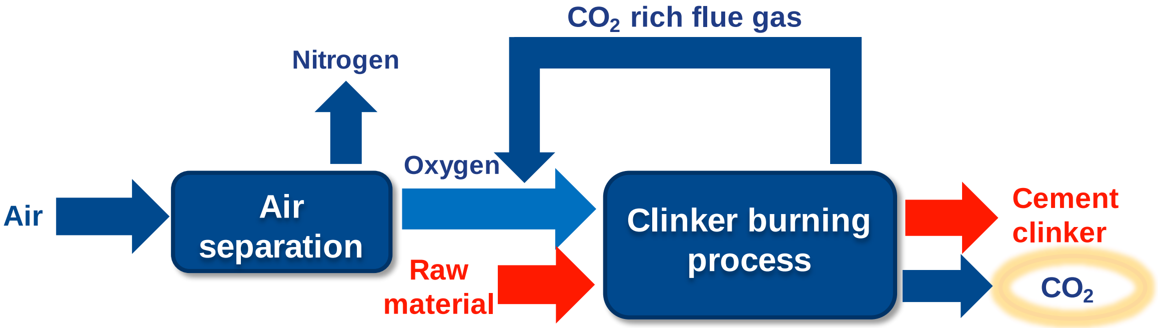

Figure 4-3 Principle of the oxyfuel technology

Different capture methods could be combined to so-called hybrid solutions, which may lead to a benefit in energy efficiency. In the cement industry a possible combination would be moderate oxygen enriched combustion - with or without flue gas recirculation - with post-combustion capture. With oxygen enrichment a certain amount of air for combustion could be replaced and/or the production capacity be increased, which leads to higher CO_2 concentration at lower volume flows in the flue gas. This results from a lower dilution from air nitrogen at a constant oxygen level in the combustion gas and a higher specific CO_2 amount from decarbonation. This would reduce the size and energy consumption of a post-combustion scrubbing unit or it would enable the use of alternative post-combustion capture technologies such as membranes, which are enhanced by the higher CO_2 concentration. Costs may therefore be reduced compared to the separate application of either post-combustion or oxyfuel technology. Based on theoretical considerations it was found that in the power sector a combination of oxygen enrichment and a post-combustion capture membrane would lead to a more efficient overall process [DAV-12]. However, the quantitative benefit of such hybrid systems has not been investigated for the cement production so far.

In the following parts of this chapter, post-combustion, oxyfuel and hybrid technologies are technically discussed. Laboratory and small scale work is described in sections 4.2-4.4 and larger scale pilot and demonstration projects are described in section 4.5.

In addition to the technical aspects, the economic framework will be decisive for future applications of carbon capture in the cement industry because all mentioned capture technologies will increase the current production costs. Accordingly costs for two competitive technologies are evaluated in chapter 4.

4.2 Post-Combustion Technologies

The application of post-combustion technologies at the clinker burning process is in an early stage of development. Several studies on the technical and economic feasibility of different carbon capture technologies for both laboratory and small-scale trials with cement-kiln flue gases have been carried out. Nevertheless, there is a need to carry out more laboratory, pilot and demonstration trials to enhance those technologies for a future application at cement kilns. Operational experiences of post-combustion technologies are available in the power sector from several pilot plants making the process well-understood. Hence the principle as an end-of-pipe technology for carbon capture has already been proven. However, the results from the power sector cannot be directly transferred to the clinker burning process because the exhaust gas composition of cement kiln flue gases is different from power plant flue gases. In principle, the following post-combustion measures could be applied at the clinker burning process:

Chemical absorption:

In general, chemical absorption is a mature technology for CO_2 capture because there are long-term experiences available from different industrial sectors, and from pilot projects in the power sector. In most cases aqueous amine solutions are used as absorbents for the CO_2.

However, the application of chemical absorption technologies at cement kiln flue gases is in a very early stage of development because only research results from laboratory or small-scale trials are available – if at all [AIF-12]. The following **Figure 4-4** shows the principle design of an absorptive capture unit.

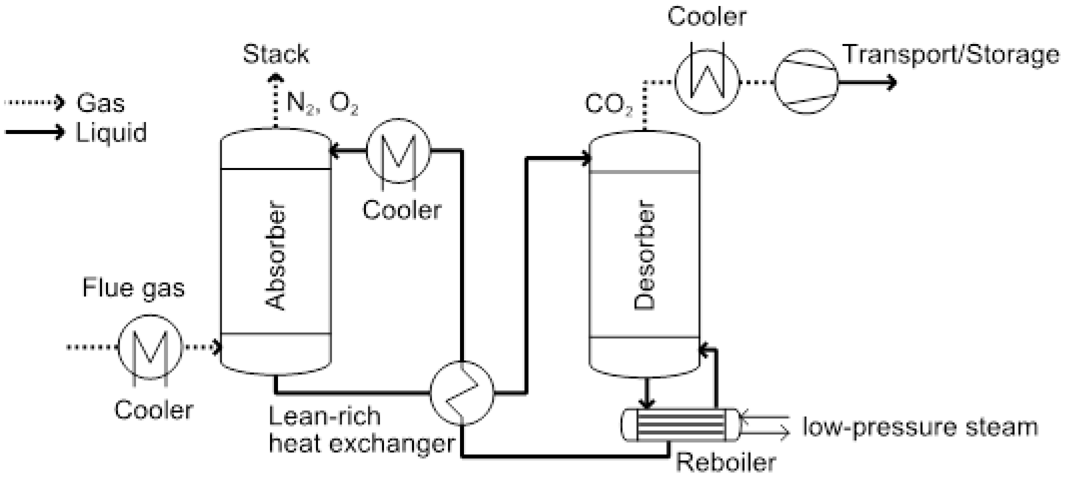

Figure 4-4 Basic design for absorptive CO_2 capture [ECR-09]

The desorption process requires a large amount of energy. Although less than 60% of the heat energy input to the clinker burning process is needed as reaction enthalpy to produce clinker, most of the waste heat could not be recovered. Waste heat from the flue gas is usually used for raw material drying, which is an essential step of the efficient kiln operation. Depending on the raw material moisture, part of this heat could be used for other purposes like reboiler duty. Moreover 10% of the heat input is lost by walls, where recovery is not applied because technology for recovery of radiation heat is unknown in the cement industry. First calculations show that not more than 15% of the required reboiler energy could be extracted from the clinker burning process [ECR-09]. For example, heat extraction of 300 kJ/kg clinker would cover only 12% of the total reboiler duty (based on a CO_2 emission factor of 1 kg CO_2/kg clinker and a total reboiler duty of 2,500 kJ/kg CO_2). Therefore, low pressure steam from a power plant in the vicinity of the cement plant would be needed to liberate the CO_2 from the absorbent. Roughly estimated the additional energy demand to produce the required steam would lead to a doubling of the specific energy demand per tonne of produced clinker. The following figure shows a potential design of a future cement kiln plant with chemical absorption technologies for CO_2 capture.

Figure 4-5 Potential design of a cement plant with chemical absorption technologies for CO_2 capture (green: nitrogen, blue: oxygen and black: CO_2) [ECRA website: www.ecra-online.org]

Membrane technologies:

Membrane technologies for CO_2 capture are still in a very early stage of development. The first small-scale trials have been carried out at power plants in the last years. However, there are no experiences about a potential application at the clinker burning process. First small-scale trials with cement kiln flue gases will be carried out in a Norwegian cement plant (see chapter 4.2.1).

Adsorption technologies:

Adsorption processes operate on a repeated cycle with the basic steps being adsorption and regeneration. In the adsorption step, gas is fed to a bed of solids that adsorbs CO_2 and allows the other gases to pass through. When a bed becomes fully loaded with CO_2, the feed gas is switched to another clean adsorption bed and the fully loaded bed is regenerated to remove the CO_2. Up to now there are no experiences available with the application of adsorption technologies at the clinker burning process, but it is planned to carry out small-scale trials at a Norwegian cement plant (see chapter 4.2.1).

Mineralisation technologies:

Several minerals and rocks have the ability to sequester CO_2 from gas streams (like the weathering process of igneous rocks). However, vast amounts of mineral materials would have to be mined, processed and returned to the ground, which requires intensive energy having a negative impact on resource conservation. A disadvantage of this process is that the CO_2 capture process is still very slow so that further research is required to accelerate the mineralisation process.

The CO_2-containing flue gases can also be treated with a basic solution to form minerals which can be stored or which can be marketed as a product. For example, a low concentration sodium hydroxide solution can be injected into the flue gas stream to form high purity baking soda ($NaHCO_3$). The SkyMine© process [SKY-13] is based on this principle, which also results in a reduction of other acidic exhaust gas components.

Up to now there are no practical experiences with the application of mineralisation technologies in the cement sector. However, in 2013 the construction of a demonstration plant was started at a North-American cement plant (see chapter 4.5).

Calcium looping:

The calcium looping process (also known as carbonate looping) is seen as a promising carbon capture technology for the power sector. During the last 15 years, many research projects and even pilot investigations have been carried out [SHI-99], [ABA-04], [ALO-10], [CHA-10], [ARI-13], [DIE-13], [KRE-13].

The carbonation process is based on the equilibrium of calcium carbonate to calcium oxide and carbon dioxide at various temperatures and pressures. In a carbonation process calcium oxide is put in contact with the combustion gas containing carbon dioxide to produce calcium carbonate in an exothermic reaction. In a subsequent calcination process the calcium carbonate is regenerated to the carbon dioxide sorbent (the calcium oxide). The carbonation could take place in-situ in the combustion chamber or in a carbonator placed in the flue gas downstream from the chamber. Currently both methods are discussed and investigated for power plants.

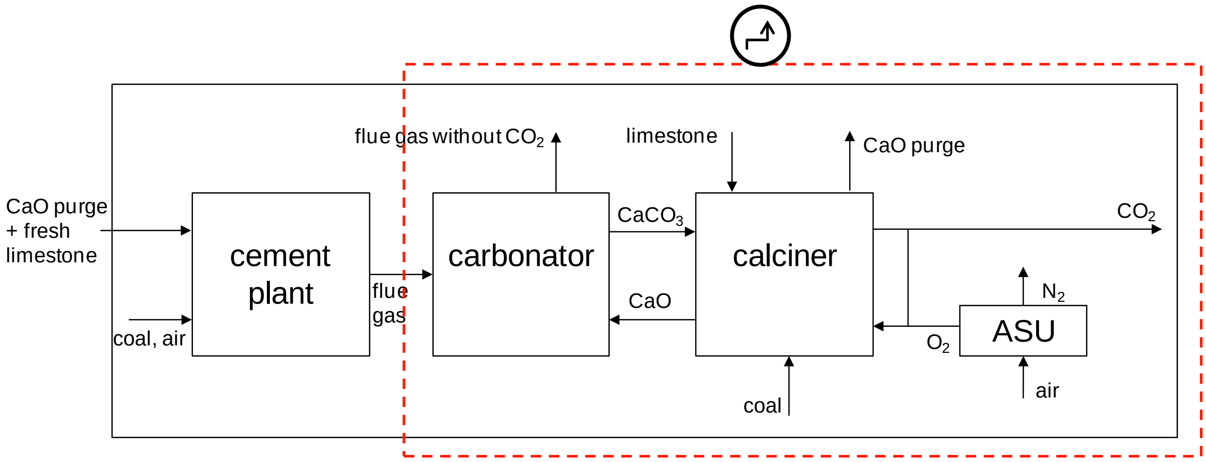

Figure 4-6 Principle of the calcium looping process [FEN-12]

With increasing number of cycles the absorption characteristics of the sorbent deteriorate so that a make-up with fresh sorbent is required. The deactivated (partly precalcined) purged sorbent could be utilized as alternative raw material in the clinker burning process – resulting in a reduction of the energy consumption and lower CO_2 emissions. Research about synergy effects between the cement industry and the power sector has been carried out recently [UST-09], [DEA-11], [ROM-12], [DEA-13], [AIF-13]. However, the calcium looping process itself could also be applied to cement kilns [BOS-09], [ROD-12], [VAT-12]. The current research activities about this issue are described in the following chapter. An interesting sideaspect of the calcium looping process is the possibility to integrate a high pressure steam cycle into the carbonator to produce electricity.

4.2.1 Research Activities

Research about the application of post-combustion technologies at cement kilns (see list in **Table 4-1**) is being carried out by different groups:

- individual cement companies, in most cases in co-operation with specialist companies for CO_2 reduction technologies
- technology providers
- universities and research organisations / institutes

Table 4-1 Research activities in the field of post-combustion capture

Activity/ Who	Scale	Technology	Status	Country/ Region	Schedule
Norcem project	Research / Pilot (~ 10,000 t CO_2 /year)	Post Combustion Capture	Initiated	Norway	2013-2017
4 sub-projects:					
- Aker Clean Carbon	Pilot	Chemical Absorption			
- RTI	Small-scale trial	Adsorption			
- KEMA / NTNU / Yodfat	Small-scale trial	Membranes			
- ALSTOM	De-risking study	Calcium looping			
Skyonic Corp.	Demonstration	Mineralisation	Initiated	USA	2013-
Technical University of Denmark / FLSmidth	Research study	Calcium looping	On-going	Denmark	2011-
Imperial College	Research study	Calcium looping	On-going	UK	
VDZ / TU Darmstadt	Research study	Calcium looping	Finalised	Germany	2010-2013
VDZ	Research study	Chemical Absorption	Finalised	Germany	2010-2012
Cemex	Pre-engineering study	Calcium looping	Finalised	USA	2010
ITRI / Taiwan Cement Corp.	Pilot	Calcium looping	On-going	Taiwan	2009-
IEA GHG	Research study	Chemical Absorption	Finalised	UK	2008
INCAR	Research study	Calcium looping	On-going	Spain	2008-
ECRA CCS Project Phases I - III	Research study	Chemical Absorption	Finalised	Europe	2007-2012

Current research activities are focussing on chemical absorption and calcium looping technologies. Furthermore, a research project has been started at a Norwegian cement plant, where different CO_2 capture technologies will be investigated within the framework of small-scale / pilot trials.

Chemical Absorption:

- VDZ, Germany has carried out a research project about the application of chemical absorption technologies. The project included not only a modelling of the absorption and desorption processes, but also trials with different amines on a laboratory level and small-scale trials in cement plants [AIF-12].
- In recent years the Norwegian cement company Norcem (HeidelbergCement Group) has carried out several studies on the applicability of post-combustion measures for CO_2 capture at the Brevik cement kiln. Some of the studies were partly financed within the framework of the ECRA CCS project [ECR-09], [ECR-12]. Furthermore, a study about the technical and economic feasibility of amine scrubbing was published in 2006 [HEG-06].
- In 2008 Mott MacDonald Ltd. executed a study concerning CO_2 capture in the cement industry on behalf of the International Energy Agency Greenhouse Gas R&D Programme. Both, post-combustion as well as oxyfuel technologies, were investigated in terms of technical issues, such as how to implement the technology in the kiln plant and feasibility of retrofitting, economic aspects and capture readiness. The study was based on MEA as solvent for the CO_2 capture. The economic impact was summarized by the increase of the production costs (ca. 97%) and the derived CO_2 abatement costs (118 €/t CO_2 excl. indirect CO_2 emissions from power production). These high costs relate primarily to the requirement of a separated combined heat and power plant. Beyond this study the necessary R&D needs were identified especially with respect to waste treatment, NO_x and SO_x removal and new technologies [IEA-08].

Calcium looping:

The potential application of the calcium looping process in the cement industry is subject of several research projects:

- The Danish Technical University (DTU) and the cement equipment supplier FLSmidth have carried out a research project on the application of the calcium looping process for de-carbonization of a cement plant [PAT-11].
- Imperial College London (Department of Engineering) have carried out studies on the principle combination of the calcium looping process at power plants and the clinker burning process. According to this, the decarbonized sorbents should be used as alternative raw material for the clinker burning process [DEA-11]. Furthermore, laboratory trials with the calcium looping process were carried out to investigate a potential enrichment of trace elements in the sorbent after repeated cycles of calcination and carbonation [DEA-13]. After that a raw meal mix was prepared to burn a clinker in a tube furnace. The produced clinker was characterised with chemical and mineralogical methods.
- INCAR in Spain (Instituto Nacional del Carbón) carried out investigations on a modified preheating of raw meal with an upstream separate combustor [ROD-08]. The CO_2

generated from the fuel combustion in the combustor would be emitted into the atmosphere, whereas the highly concentrated CO_2 gas stream from the precalciner could be compressed and transported to a storage site. Using this method, the CO_2 emissions from a cement plant could be reduced by 60%.

- VDZ, Germany carried out a research project on the utilization of deactivated sorbents from a calcium looping process in coal-fired power plants in a clinker burning process [AIF-13]. It turned out, that the waste sorbent could be used in the clinker burning process as alternative raw material. The composition and the properties of produced clinker met the most important requirements for the subsequent production of a laboratory cement. Additional calculations with an existing process model for the clinker burning process showed that the alternative raw material substitution rate had to be limited and should be below 30%. Nevertheless, a CO_2 reduction of up to 34% could be achieved, if 30% of the raw material is substituted by theses waste material.
- Cemex USA carried out a study on the application of the calcium looping process at the Odessa cement plant in Texas [GAR-10]. It was planned to capture 160,000 – 180,000tCO_2 per year. Geological assessments of potential storage sites were conducted resulting in a positive evaluation. The plant is located in the vicinity of oil wells so the reuse of CO_2 for enhanced oil production was considered. Furthermore, a CO_2 pipeline is available close to the plant so that the transport of CO_2 to a local storage site would be a viable option. However, in 2010 the project was stopped due to the high technological risk and high costs.
- Industrial Research Technology Institute (ITR) in Taiwan has carried out a research project to investigate the Calcium looping technology for cement plant flue gases in several steps since 2009. Based on fundamental testing in thermogravimetric analysis (TGA) two generations of bench-scale systems had been operated before transferring the system to pilot scale (see section 4.5). The first generation was a fluidized bed carbonator (FBC) and a furnace for calcination in batch operation. The second generation was a continuously operated FBC with a rotary kiln for calcination achieving a calcination efficiency of 90%. In 100hr continuous operation a CO_2 removal of ca. 85 % from the flue gases was acheived [CHO-13].

Brevik Project:

The Norwegian cement company Norcem applied successfully for funding to construct a test centre for post-combustion capture trials. GASSNOVA, a state-owned Norwegian company, will grant a 75% funding to a total budget of 11.7 Mio. € [BJE-13]. The project duration is from May 2013 until March 2017.

The European Cement Research Academy (ECRA) is also involved in the project and will contribute to the dissemination of the results into the European cement industry.

The test centre will be built in the Brevik cement works. It offers the possibility to conduct several small-scale or pilot trials with cement kiln flues gases [BJE-13]. The test site will provide the required infrastructure to carry out several post-combustion capture trials in parallel. The following companies and technology providers are involved in the Brevik project:

- Aker Solutions (former Aker Clean Carbon) will install a mobile test unit and will carry out pilot trials with amine scrubbing.

- The American Research Triangle Institute (RTI) will carry out dry adsorption trials with specialised polymers. The elimination of water results in an improved energy efficiency compared to the amine scrubbing process.
- A consortium consisting of the Dutch company KEMA, the Israeli engineering company Yodfat and the Norwegian University of Science and Technology (NTNU) will carry out small-scale trials with membrane technologies.
- ALSTOM is involved with a de-risking study about the application of the calcium looping process (regenerative calcium cycle technology / RCC).

4.2.2 Evaluation of the technology

According to the current state of knowledge, post-combustion capture technologies could be applied to the clinker burning process. Chemical absorption is the most mature measure for potential application at cement kilns. Remaining open questions, e.g. about solvent degradation, do not question the applicability in principal. However, the energy demand of the whole capture process is high and could amount to 2,700 - 3,500 kJ/tCO_2. By this, the specific energy demand per tonne of produced clinker would be doubled including the energy for reboiling. Low-pressure steam, which is needed for the desorption process, could be supplied by a power plant in the vicinity of the cement plant. The waste heat potential of the clinker burning process could be used in some locations, but is insufficient (ca. 400 - 850 kJ/t CO_2) to provide enough heat to the reboiler for capturing high levels of the CO_2 emissions [AIF-12].

Preliminary theoretical considerations indicate that the integrated calcium looping process might have a lower energy penalty. Furthermore, a steam cycle could be integrated to produce electrical energy. Another advantage of the calcium looping process is the type of sorbent which is available in all cement production works. Membrane and adsorption technologies are still immature so that an evaluation about a future application is not possible. First operational results will be achieved within the framework of the Brevik Project so that a sound assessment can be made by 2016/2017.

4.3 Oxyfuel Combustion

The oxyfuel technology relies on the combustion of pure oxygen and a recirculation of flue gas in order to enrich CO_2 to an amount which allows a relatively easy purification by liquefaction systems. For this purpose different integration systems can be chosen, the full and the partial oxyfuel technology.

Implementing the full oxyfuel concept almost all generated CO_2 can theoretically be captured. In this case the whole plant is operated under oxyfuel conditions. Therefore, all plant units are influenced by the changed gas atmosphere. The heat transfer, the combustion, the capacity streams of material and gas as well as the clinker formation are affected due to the different gas properties like heat capacity, emissivity or density.

Within a joint research project of the European Cement Research Academy (ECRA) a full concept of an oxyfuel cement plant has been developed [ECR-09]. The principal configuration of this design uses the conventional technology as the starting point (see **Figure 4-7**). The main additional installations required for the oxyfuel kiln are:

- two stage clinker cooler (first stage operated in oxyfuel mode, the second one in air mode)
- exhaust gas recirculation system
- gas-gas heat exchanger (optionally, a gas-steam heat exchanger)
- condensing unit
- air separation unit (ASU)
- CO_2 purification unit (CPU)
- rotary kiln burner for oxy-combustion

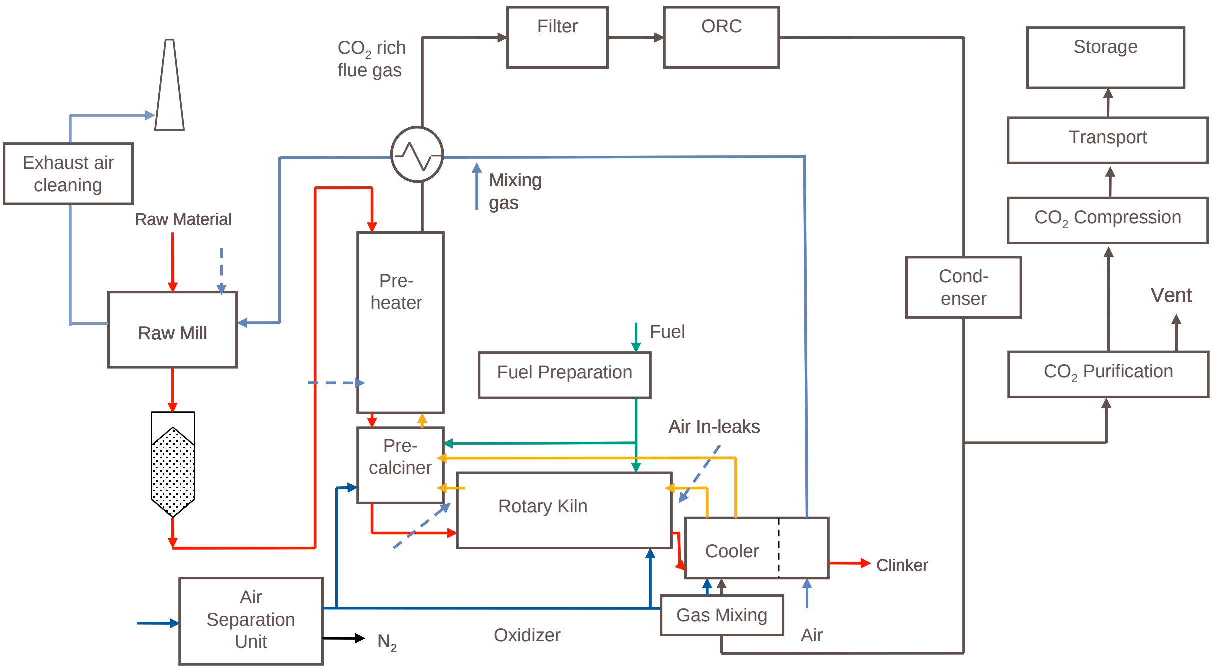

Figure 4-7 Configuration of a full oxyfuel cement plant [ECR-09]

Clinker cooler: The first cooler stage is operated with recycled flue gas, which is needed in the burning process. As this would result in still too high clinker temperatures, a second cooler stage, which is operated with ambient air, is considered. The air leaves the cooler as exhaust air and can be used for raw material drying or fuel preparation. A major advantage of using cooler exhaust air for drying purposes is the fact that e.g. the raw mill must not be operated under air-tight conditions.

ASU: The oxygen from the ASU mixed with the recirculated CO_2 rich exhaust gas is forming the so-called oxidizer. This is provided to the precalciner and kiln firing (as primary “air”) as well as to the premixing of cooling gas. For a medium-size cement plant with a kiln capacity of 3,000 tpd the oxygen demand is estimated to be around 30 to 35 tph. Such amounts of oxygen can for logistical reasons only be provided by an on-site oxygen supply system.

Recirculation/heat exchanger/condenser: Within the recirculation the flue gas undergoes different steps like the removal of heat, dedusting and dehydration. Part of the flue gas is discharged to the CO_2 purification unit (CPU) and the residual fraction to the cooler for another cycle. Heat from the flue gas, which is leaving the preheater, could also be used to increase the drying potential of the cooler exhaust air by a gas-gas heat exchanger. If the flue gas still contains enough energy, power can be produced by either an Organic Rankine Cycle or KALINA process.

The partial oxyfuel concept concentrates the oxyfuel operation only on the calciner, which is separated from the kiln units of the plant. In the case of a double line preheater tower one line could also be switched to oxyfuel operation. This concept takes advantage of the fact that most of the CO_2 emissions are generated in the calciner by a major part of the decomposition of carbonates (responsible for approx. 60% of CO_2 from cement plants) and fuel input (ca. 60% of total fuel input). As the other installations (kiln, cooler, raw mill) are operated conventionally, this option avoids the increased effort involved with the improvement of seals and does not have any impacts on the product quality. Due to fewer changes to the kiln plant design and reduced influence on the plants operation this concept is seen preferably for retrofitting purposes. However, by encapsulating the calciner the usual capacity stream ratio of the plant is disturbed resulting in higher energy demands in the main burner, where CO_2 remains unabated. This circumstance and losses by the CPU lead to an overall capture rate of this technology of 60%. Therefore the capture efficiency is lower compared to full oxyfuel operation of the clinker burning process (>85%).

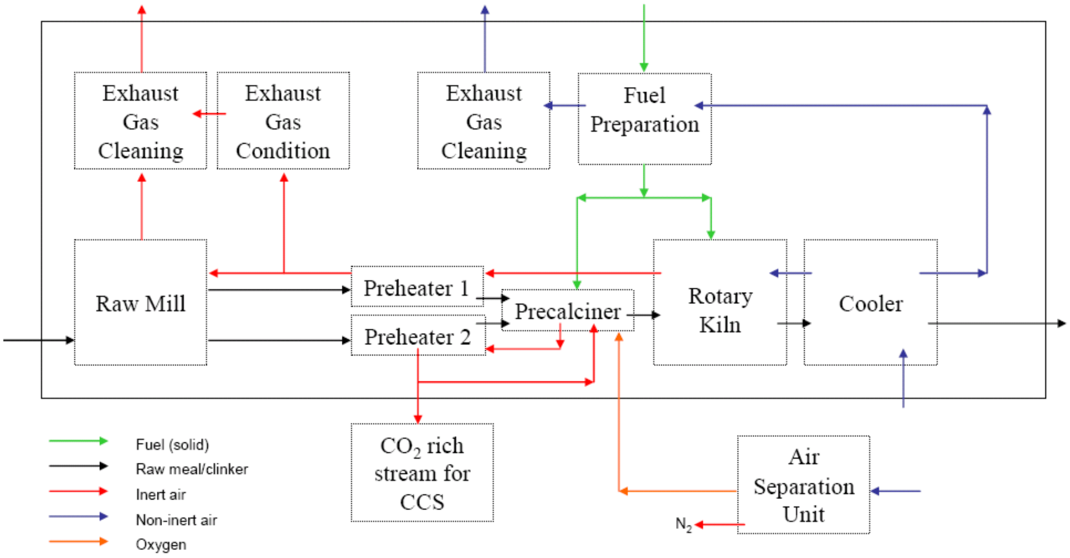

Figure 4-8 Configuration of a partial oxyfuel cement plant [IEA-08]

Exemplary for the partial oxyfuel technology the configuration of [IEA-08] is explained more in detail in the following (see **Figure 4-8**). Oxygen from the air separation unit is supplied premixed with recycled flue gas before being provided to the calciner. Here the preheated material from both preheater strings is calcined and then supplied to the kiln for further mineralogical conversion. Gas from the calciner, which is enriched by CO_2 from the material and combustion gases, is provided to preheater string 2. Preheater string 1 is operated with combustion gases from the rotary kiln. These combustion gases can be used for the drying of raw material. After this usage it is released to the environment, while the oxyfuel string gases are captured. As tertiary air from the grate cooler is provided to the calciner as usual, it can be used for other issues like preheating, drying or power generation.

4.3.1 Research Activities

The compilation of research activities in the field of oxyfuel technology in the cement industry has been elaborated on the basis of literature studies and surveys amongst industry and supplying industry. **Table 4-2** lists the identified projects and patents, which imply some previous considerations.

Table 4-2 Research activities in the field of oxyfuel technology

Activity/ Who	Scale	Technology	Status	Country/ Region	Schedule
ECRA CCS Project – Phase IV	Research (concept study for pilot testing)	Oxyfuel	On-going	Europe	2013 - 2014
KHD	Patent filing	Oxyfuel	Application	International	2011
Thyssenkrupp Resource Technologies (Polysius)	Patent filing	Oxyfuel (Partial)	Application	International	2010
Fives FCB	Patent filing	Oxyfuel	Application	International	2010
Cementos Argos/ Universidad Nacional de Colombia	Research (modelling)	Oxyfuel	On-going	Colombia	2010 -
CIUDEN/Oficemen	Research/ Pilot	Oxyfuel	Stopped	Spain	2010 -
TUHH/ ThyssenKrupp	Research (concept study)	Oxyfuel	Finalized	Germany	2009 - 2013
IEA GHG	Research study	PCC and Oxyfuel (Partial)	Finalized	UK	2008
Lafarge	Patent filing	Oxyfuel (Partial)	Application	International	2008
AirLiquide	Patent filing	Oxyfuel (Partial)	Application	International	2008
ECRA CCS Project Phases I - III	Research (concept study/ modelling/ lab tests)	PCC and Oxyfuel	Finalized	Europe	2007 -2012
VDZ	Research (modelling / lab tests)	Oxyfuel	Finalized	Germany	2007 - 2012
Zeman/ Columbia University	Research (concept study)	Oxyfuel	Finalised	USA	2006 - 2009

Most of the research projects are smaller studies, which have been initiated since 2007. These studies mainly examine basic research on the applicability of the oxyfuel technology to the clinker burning process and its impact on the process. Only a few projects are still ongoing like the modelling work of Cementos Argos in cooperation with Colombian universities and the CCS project of ECRA. With the progress of this basic research some patents have been filed. The listed projects are briefly described in the following context:

ECRA CCS Project:

In 2007, the European Cement Research Academy launched a long-term CCS research project, which comprises different phases. The project is funded by ECRA members and industrial project partners such as technology manufacturers and gas suppliers. Phase I was finalized in spring 2007 and provided a first overview of CCS and its potential implications which can be applicable in the cement industry [ECR-07]. Four options for capturing CO_2 were evaluated: Pre-combustion, post-combustion, oxyfuel technology and calcium looping. As a result oxyfuel and post-combustion (chemical absorption) technologies were assessed to be more appropriate for the potential application at cement kilns than pre-combustion or calcium looping.

The main objective of phase II was to perform a more detailed study for CO_2 capture as applied to the clinker burning process which focused on oxyfuel and post-combustion measures. The research activities of post-combustion capture methods focused on investigations regarding solvent regeneration, flue gas characteristics, plant layouts, cost estimations, oxygen supply, process modeling, CO_2 purification and compression. Concerning the impact of the oxyfuel operation on kiln operation and chemical-mineralogical product reactions, basic results could be derived from process modeling and laboratory tests. A process design with regard to the application of full oxyfuel technology was developed, as presented in section 4.3 [ECR-09].

Phase III started in autumn 2009 and deepened the research based on the theoretical findings involving specialized companies in different fields of expertise. The work packages on oxyfuel technology aimed for a better understanding of this technology when applied to existing kilns. The focus was laid on optimised sealings and refractories, burner and cooler design, and the CO_2 purification unit (CPU) design. Finally, the impact of oxyfuel operation on clinker and cement quality was investigated [ECR-12]. The main overall conclusion of phase III was that oxyfuel technology might have a higher potential than previously expected in terms of its application to existing kilns. Even though there are many questions which need to be investigated in more detail, it became clear that under these circumstances the focus of a phase IV should be on oxyfuel. For that reason the current phase IV deals with the further development of a theoretical 3,000 t/d kiln plant, but places the emphasis on a concept study of an oxyfuel pilot plant. Work packages are the design and dimensioning of the plant, control and safety concepts as well as cost estimations.

IEAGHG:

In 2008 Mott MacDonald Ltd. executed a study on CO_2 capture in the cement industry on behalf of the International Energy Agency Greenhouse Gas R&D Programme. Both, post-combustion as well as oxyfuel technologies, were investigated in terms of technical issues, i.e. how to implement the technology in the kiln plant and feasibility of retrofitting, economic aspects and capture readiness. The oxyfuel technology was considered as higher technical risk solution for carbon capture. A process analysis of mass and heat streams provided an optimum concept for implementation. In the case of oxyfuel the highest potential was identified in the partial oxyfuel technology especially concerning the suitability of retrofit. The economic impact was summarized by the increase of the production costs (oxyfuel ca. 24 %)

and the derived CO_2 abatement costs (35.8 €/t CO_2 excl. indirect CO_2 emissions from power production). Issues like space requirements and minor modifications at the kiln plant were shown to be important to make the plant capture-ready for retrofit. Beyond this study the necessary R&D needs were identified especially with respect to the process inside the kiln plant (heat transfer, optimum O_2/CO_2 ratio), refractory, product quality and optimized operation [IEA-08].

Technical University of Hamburg-Harburg, Germany:

The Technical University of Hamburg-Harburg, Germany carried out a research project about the potential of CCS technologies for reducing CO_2 emissions in cement production in the years 2009 to 2013. The project was funded by the cement plant manufacturer ThyssenKrupp Resource Technologies. The study covered both capture methods: post-combustion and oxyfuel technology but with a strong focus on the latter. For this purpose different integration concepts of the oxyfuel technology into the clinker burning process were evaluated in terms of energy efficiency, capture rate and CO_2 purity. These concepts – partial and full integration, with or without heat recovery - were compared using thermodynamic modeling. Although all considered concepts show a significant potential to decrease CO_2 emissions, the electrical energy demand is significantly increased by the ASU/CPU. The highest reduction potential at the lowest fuel energy demand per unit of emission reduction was the full integration concept as presented in ECRA phase II [OBE-11]. Based on that evaluation the most realistic and practical application will be analyzed concerning costs, retrofitting etc. and subsequently compared to a post-combustion capture. The further work focuses on the development of strategies for the enhancement of capture rate, reduction of electrical and fuel energy demand. A final report has not yet been published [TUH-13].

F. Zeman, Earth Institute at Columbia University:

Frank Zeman, who is focusing on the sustainable use of energy, presented the first detailed theoretical approaches to a “Zero Emission Kiln” using the oxy-combustion technology in 2006 [ZEM-06]. The concept was enhanced in the following years. Small-scale experiments on the impact of CO_2 atmosphere on the clinker production especially on the calcination showed an impairment of the calcination but no influence on the clinker formation [ZEM-08]. The modifications to the plant components were sketched on the basis of the full oxyfuel concept. He pointed out that oxy-combustion offers some possibilities to increase energy efficiency to potentially decrease the amount of generated and therefore captured CO_2 [ZEM-09].

Cementos Argos, Universidad Nacional de Colombia and Universidad de Antioquia:

In line with their research objectives to reduce CO_2 emissions the Colombian cement producer Cementos Argos initiated a project with the Universidad Nacional de Colombia and Universidad de Antioquia. The objective is to investigate the impact of oxyfuel operation on the kiln plant in order to understand what a future cement kiln could look like [BER-12].

The focus was on the impact on kiln burner characteristics. Experimental investigations were made to determine combustion features. CFD in combination with thermodynamic modeling showed the influence of the recirculation rate and oxygen content on the adaption of kiln operation especially on the flame formation and heat transfer mechanism. The models were able to predict flame temperatures, the energy transfer to the bed, the flame length and other important aspects of the process. The simulation showed that oxyfuel technology with flue gas recirculation could even provide a benefit for the cement manufacturing. It was demonstrated that a short dense flame is obtained, whose high energy density encourages the production process [GRA-11].

Based on that project the Process and Energy Department of the Universidad Nacional de Colombia indicates to initiate further research in cooperation with other universities on fluidized bed combustion in oxyfuel operation. The part of the results should also be applicable to burning systems for cement production.

VDZ, Germany:

The research project of the VDZ, which was funded by the German government, focused on the simulation of kiln plant operation as well as on the impact on product quality [Hoe-10]. A comprehensive simulation study based on a numerical process model of the full oxyfuel concept determined the impact of the recirculation rate and oxygen concentration on the heat transfer, temperature profiles, energy demand and clinker composition. Irrespective of the retrofitting aspect, the technology offers additional opportunities to influence the operation of the kiln plant, the fuel energy demand and the concept for the waste heat recovery [KOR-13]. The basic outcome was that the optimum setting of a recirculation rate strongly depends on the local boundary conditions of a specific plant site (e.g. raw material moisture).

CIUDEN/Oficemen, Spain:

In 2010 the association of Spanish cement manufacturers, Oficemen, and the Spanish organization CIUDEN (Fundación Ciudad de la Energía) signed a collaboration agreement in order to enhance the research and development of technologies of capture and storage of CO_2 and demonstrate the feasibility of its application in the cement industry [OFI-10]. Within this collaboration joint activities of research and technological development, as well as training and dissemination involving higher educational institutions are intended.

Based on CIUDEN’s experience with their pilot facility, a 30 MW_{th} CFB boiler in oxyfuel operation, a cement oxyfuel pilot kiln was planned, but due to the lack of funding it was suspended.

Patents:

Based on early theoretical considerations some patents were applied for filing. The patents of the French cement producer Lafarge (WO 2008/059378 A2) and the gas supplier Air-Liquide (WO 2008/056068 A1) refer to the isolation of CO_2 enriched gas produced in the precalciner. In Lafarge’s patent the precalciner’s gas streams are completely separated from other plant aggregates in contrast to the partial oxyfuel concept presented in [IEA-08], where at least one preheater line is included in the oxyfuel operation. Using a nearly pure oxygen stream for combustion to calcine the raw material a CO_2 rich flue gas is generated, which will be isolated for storage. Different precalciner concepts with and without recirculation of flue gas are described. In 2010 ThyssenKrupp Resource Technologies, former Polysius, (WO 2010/046345 A1) expanded this process by using a fluidized bed as the precalciner.

The plant manufacturer Fives FCB claims two different concepts of flue gas recirculation for CO_2 enrichment and separation (WO 2010/012881 A1). The flue gas can either be recirculated to the preheater, the calciner or the cooler. The latter one includes a cooler exhaust gas containing CO_2, which will be recirculated to the cooler inlet after removal of heat. In contrast to the full oxyfuel concept in [ECR-09] the cooler will not be split. Based on the splitting of the cooler for recirculation purposes KHD Humboldt Wedag (WO 2011/029690 A1) added a heat exchanger in the mill circuit to benefit the raw material drying by increasing the available energy from the cooler exhaust air by a heat exchange with the flue gas from the preheater.

4.3.2 Evaluation of the technology

The described activities on oxyfuel technology in the cement industry point out that there has been a lot of basic research including concept developments, laboratory tests and modelling work in the past few years. Each study covered different aspects of the application at a basic level. However, most of the studies complement each other. The studies of F. Zeman (Columbia University), TUHH and IEAGHG showed different conceptual solutions for the application of oxyfuel to a cement plant. While the Colombian project limits the scope of investigation mainly on the understanding of rotary kiln operation especially concerning the flame formation. Studies undertaken by VDZ and ECRA gave another insight in the kiln operation depending of process parameters like the recirculation rate. The impact on the chemical-mineralogical material reaction and on the cement properties are discussed in [ZEM-08] and [ECR-12].

One issue all studies have in common is the statement that the optimized oxyfuel technology exhibits benefits in terms of thermal energy efficiency or NO_x reduction compared to other capture methods but R&D is still needed. Moreover the listed patents show basic concepts, and highlight the interest of the industry in this capture technology. [ECR-12] showed approaches to clarify more technical issues related to false air ingress, suitable refractories, CO_2 -purification, burner and cooler design. Nevertheless investigations at a pilot plant are crucial to take the next steps towards commercial realisation. Notably, there is currenlty no information available on pilot plants.

On the basis of the reported research studies two reasonable technologies crystallize. Both the partial and the full oxyfuel technology seem technically feasible. Although the full oxyfuel concept influences the whole clinker production, the most significant influence on the material reaction is the shifting of the calcination reaction. On the assumption that the mineralogical clinker formation remains unrestricted by higher CO_2 concentration in the burning atmosphere [ZEM-08, ECR-12], the material conversion is equally important for both partial and full oxyfuel.

The partial oxyfuel technology has been recommended as an option specifically for retrofitting existing cement plants [IEA-08]. However, parts of the plant like the precalciner and preheater have to be adapted or even replaced due to the changed gas properties and volume flows. Systems for transferring material without any gas exchange have to be developed at the connection points between the precalciner and kiln. The recirculation piping has to be established making a separation of the fan system of the two preheater strings necessary. Moreover the isolation of the precalciner requires a suitable waste heat recovery system. At least two heat exchangers, which are operated under high dust loads, have to be implemented. This would result in considerable engineering work.

Unexpectedly, recent research showed that the full oxyfuel operation is applicable to existing cement kilns as well as new ones [ECR-12]. The operation of such plants may be feasible, although the setting of process parameters like the recirculation rate are limited in these cases. The plant requires modifications at the burner and the two-stage cooler as well as an adaptation of refractory lining. Different designs of two-stage coolers using dynamic separation parts are able to fulfil the task of gas separation and can be retrofitted relatively easily. Burners adapted to oxyfuel gas streams can also be retrofitted without large modifications to the plant. Refractory lining could be changed with the usual replacement interval. Although the issue of “false” air ingress attracts more notice in the full concept, it is also an issue for the partial oxyfuel technology as a significant part of the false air intrudes into the system in the preheater area. In comparison to current practice, the complexity of operation increases in both partial and full oxyfuel cases.

Using oxyfuel the electrical energy demand rises due to the energy intensive air separation and CO_2 purification. In partial oxyfuel operation only oxygen, which is needed for the combustion of fuel in the precalciner, has to be produced. As only part of the generated flue gas is captured the volume flow for purification is reduced respectively. In conclusion the partial oxyfuel technology requires less electrical energy than the full concept. On the other hand the complexity of waste heat recovery rises and the necessary heat exchanger lowers the energy efficiency of the total oxyfuel cement plant. Thus the thermal energy demand is increased, while in the full oxyfuel concept the whole potential of oxygen enriched combustion could be utilized. In summary the total energy demand of both concepts is comparable. In full oxyfuel operation the specific CO_2 emissions generated from fuel are lower at simultaneously higher indirect emissions due to the higher power demand.

The full oxyfuel concept is theoretically able to capture the total amount of generated CO_2. A decrease of the capture rate depends on the CPU efficiency, which in case of liquefaction limits the capture rate at least to 90%, on leakages of gas at the two-stage cooler and potential additional firing for the issue of raw material drying. Thus the capture rate could be determined between 85 and 99% (changing the CPU technology). The partial oxyfuel concept allows the capture of around 60%, as only the flue gas from the precalciner line is treated additional to the reduction of capture efficiency due to the CPU performance.

Both concepts offer advantages and disadvantages, so there is not a clear preference to one concept. For this reason both concepts are evaluated in terms of economic and technical barriers in section 4. The patents described in this study represent different designs of both of the oxyfuel concepts, they are not sufficiently detailed to be investigated further in this study.

4.4 Hybrid capture technologies

Hybrid systems are based on the combination of different capture methods like post-, pre-combustion and oxyfuel technology. Using a combination in a hybrid system could deliver synergies where the respective advantages of the separate systems could be exploited.

A feasible concept for the cement industry is the combination of oxy-combustion with post-combustion technology. The utilization of oxygen in the system allows higher CO_2 contents in the flue gas as dilution by nitrogen from air is reduced. Therefore, the hybrid concept relies on the fact that less sorbent is required when the CO_2 content in the flue gas is higher. Thus the energy demand for desorption is reduced. Moreover, this increased concentration enables the application of different technologies for separation like membranes, which consume less energy. Hybrid systems are aimed at an optimal operational mode at the highest overall energy efficiency, which depends on:

- Kiln operation and thermal energy efficiency
- Electrical energy demand by oxygen supply
- Efficiency of scrubbing process

Some information is available about so-called ECO-scrub systems. These systems use a combination of oxy-combustion and post-combustion scrubbing in the power sector, which may lead to approx. 28.5% reduction in energy demand for the reboiler [DAV-12]. Due to the interdependencies of factors detailed calculations are necessary to assess the concept and its possible benefits for the cement sector.

Different application scenarios are considered:

- Post-combustion capture combined with oxygen enrichment without flue gas recirculation
- Post-combustion capture combined with oxygen enriched operation with partial flue gas recirculation
- Post-combustion capture combined with full oxyfuel operation including flue gas recirculation

Retrofitting hybrid systems should be feasible with an equivalent level of modification as would be necessary for oxyfuel operation. In all of the described scenarios the oxygen has to be supllied depending on the enrichment level by either an air separation unit or by tank receipt from an external oxygen plant. Moreover the oxygen infrastructure (piping, injection etc.) has to be added. To implement a flue gas recirculation system, piping, fans and connections have to be included. As and end-of-pipe technology the post-combustion capture unit could be connected to existing cement plants, which inturn determines the capture rate.

Post-combustion capture/ oxygen enrichment without flue gas recirculation

Using oxygen enrichment of the combustion gas (secondary and tertiary gas) the production capacity, and simultaneously, the energy efficiency could be increased (see section 3.1.1). From this, results higher CO_2 concentrations in the flue gas due to further calcination of raw material, lower fuel input compared to the reference case and less nitrogen in the combustion gas. Typically, the flue gas from cement kiln plants contains 15 to 30 vol.% CO_2 depending on the operation, the design, fuel type or false air ingress. Membranes for CO_2 separation are still at the research and development state. However an efficient operation is predicted at CO_2 concentrations of above 20 vol.% [DAV-12]. In many cases this boundary condition is already achieved, but could be enhanced by moderate oxygen enrichment.

A numerical simulation, executed by VDZ, determined an increase of CO_2 concentration of 2.5 vol.% by an oxygen enrichment to 23 vol.% in the combustion gases. From this the scrubbing process is expected to be more efficient or a switch between post combustion technologies (scrubbing vs. membranes) would become possible. Furthermore, using oxygen enrichment without flue gas recirculation the impairment of the membrane operation by the application of alternative fuels, which may reduce the CO_2 concentration due to lower carbon contents, false air ingress becomes less important. However, large savings in energy by using e.g. amine scrubbing systems are not expected by this slight increase of CO_2 concentration.

Moreover the specific thermal energy demand of the kiln plant could be reduced by approx. 2% due to the increase of production capacity of 9.5%. On the other hand this measure causes an increase of electrical energy demand due to the oxygen supply by an air separation unit. The specific volume flow of the flue gas is reduced (ca. 7%), which gives another benefit in terms of size and pumping for the post-combustion capture. Specifically for each kiln system the oxygen content could be further increased in the combustion gas. In principle the maximum oxygen concentration is limited by peak temperatures in the sintering zone resulting in thermal stress on refractory and kiln walls.

Post-combustion capture/ oxygen enriched operation with partial flue gas recirculation

A further CO_2 concentration increase could be achieved by a limited flue gas recirculation (compare **Figure 4-9**). It is desirable to avoid comprehensive modifications to the kiln plant so the partial oxyfuel system seems to be the most efficient solution for this purpose. This is because only another piping system has to be added to the conventional plant. The plant is also operated with oxy-combustion, but small portions of the flue gas can be recirculated to the precalciner to increase the CO_2 concentration in the flue gas. Part of the tertiary air is therefore replaced by flue gas. The more tertiary air is replaced the higher the resulting CO_2 concentrations. However, substituting tertiary gas of about 900°C in higher portions by recycled flue gas of about 350°C will make preheating of the recycled flue gas necessary in order to keep the precalciner combustion running. A heat exchanger between tertiary air and recycled flue gas could be installed. Using this type of system, the CO_2 concentration could be increased to at least 50 vol.%. Waste heat from the cooler exhaust gas could be used for either raw material drying or preheating of the oxygen.

In this case the recirculation of gas at a lower temperature level would lead to a decrease of thermal energy efficiency of the kiln plant. The benefit of oxy-combustion is then compensated by the negative influence of the recirculation on the thermal energy demand.

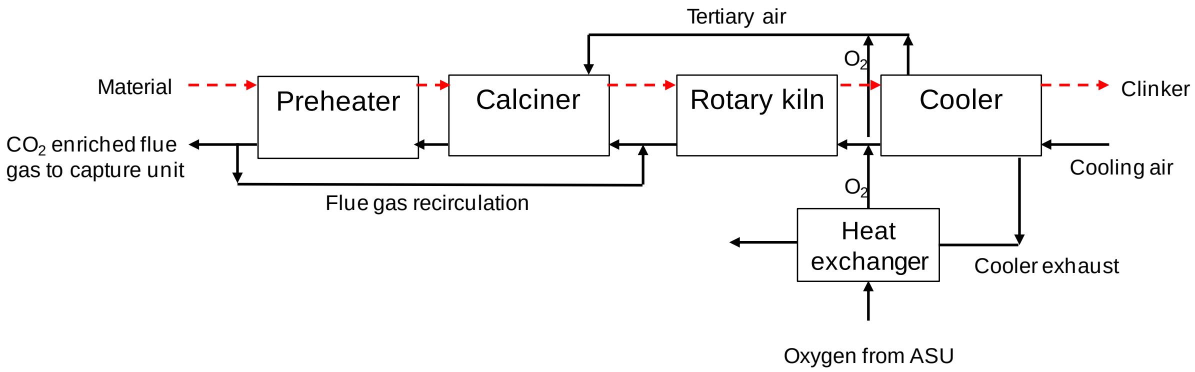

Figure 4-9 Concept of a hybrid system of oxy-combustion with limited flue gas recirculation and post-combustion capture

On the other hand NO_x emissions could potentially be reduced by flue gas recirculation as the recurrence of NO_x to a combustion zone could force its reduction to nitrogen. High NO_x contents in the flue gas lead to a degradation of the sorbents like amines and therefore cause higher operating costs by replacing the sorbent. Therefore secondary NO_x removal techniques, which may become necessary for the scrubbing process, could be avoided by recycling flue gas.

Post-combustion capture with full oxyfuel operation including flue gas recirculation

Even higher CO_2 concentrations in the flue gas require advanced modifications at the kiln plant towards absolute oxyfuel application and make a post-combustion system redundant as the CO_2 could be purified by the less energy intensive liquefaction. Although, the application of the full oxyfuel concept including the recycling of CO_2 to the cooler would influence the whole plant and requires the adaptation of the cooler, which would involve an effort too high just to concentrate the CO_2 in smaller amounts.

In essence, changing the system to pure oxyfuel operation in combination with post-combustion capture seems to be uneconomic because the liquefaction purification of CO_2 is less energy intensive.

4.4.1 Research Activities

No research activities with regard to the application of hybrid systems for carbon capture in the cement sector have been published yet.

4.4.2 Evaluation of the technology

Due to the lack of research results in the field of hybrid systems an evaluation of the technology could not be provided yet.

4.5 Demo/ Pilot projects in CCS

According to the IEA’s CCS roadmaps [IEA-11, IEA-13], the cement industry is one of the most significant industrial sectors with high CO_2 emissions. Pilot and demonstration projects are indispensable to develop carbon capture for this major CO_2 emitting sector.

However, only a few pilot and/or demonstration projects have been started or initiated. It is obvious that improved funding would be required to pave the way for carbon capture in the cement industry. The following pilot and demonstration projects have already been started:

Taiwan Cement Corp.:

The first carbon capture pilot project in the cement industry was commissioned in June 2013 [TAI-2013]. The project is being carried out as a co-operation between Taiwan Cement Corp. and the Taiwanese Industrial Technology Research Institute (ITRI). The CO_2 capture from a cement plant and a power plant will be achieved with the calcium looping process. The pilot plant has a capture capacity of 1 t CO_2 per hour. The inactive sorbent (0.1 – 0.3 t/h) will be reused in the cement process. Waste heat from various sources will be used to produce electricity and steam and to preheat coal, air and oxygen.

According to current cost estimations, the capture costs could be around 26 US-$/t of CO_2 [TAI-2013]. In the future, the captured CO_2 will be pumped underground and will enhance the production of natural gas. Furthermore, the reuse of the captured CO_2 is considered, e.g. for biodiesel production. The next steps towards demonstration scale have already been planned [CHO-13].

Skyonic Corp.:

In June 2013, the American company Skyonic Corp. disclosed that it will get a 128 M$ funding from private investment companies and a further grant of 28 M$ from the Department of Energy for the construction of a carbon capture demonstration plant with the so-called “SkyMine” process in Texas. The plant is currently under construction at Capitol Aggregates Cement in San Antonio and will be able to capture 83,000 t CO_2/y from the cement plant as well as acid gases and heavy metals. The CO_2 is mineralized to sodium bicarbonate which can be sold on the market [CCJ-13], [SKY-13].

ECRA:

ECRA’s CCS research project is currently in phase IV.A. The main objective is to carry out calculations and modelling about oxyfuel combustion at cement kilns. Furthermore a plant layout is to be developed. The forthcoming phases V and VI envisage the organisation of pilot and demonstration trials, in the period between 2015 and 2020. However, a decision about the future project phases will not be made before the end of phase IV (summer 2014).

Norcem A.S.:

The Norwegian cement company Norcem will start pilot trials with different carbon capture technologies in 2014 (project duration: May 2013 – March 2017). The trials will be carried out in the Brevik cement plant in southern Norway. A funding of 75% was granted by the state-owned institution GASSNOVA.

It is planned to install a test site where different post-combustion technologies can be investigated simultaneously, e.g. chemical absorption, adsorption and membrane technologies. At a later stage also Calcium looping technology will eventually be tested. All the pilot trials will capture the CO_2 and release it into the atmosphere afterwards. There are no plans to store or to reuse the captured CO_2.

Pond Biofuels / St. Marys Cement:

The Canadian company Pond Biofuels is capturing CO_2 emissions from a cement plant by using algae. For which purpose they have designed, constructed, and are operating a large scale process validation facility on a basis of a photobioreactor of 1,500 square foot facility. The trial is carried out at St. Marys Cement in south-western Ontario [BWM-12].

Lafarge / Mantra:

Another small-scale project is planned for Lafarge Cement in Richmond, Canada. The company Mantra Energy is designing a pilot project to capture 100 kg of CO_2 per day. The so-called ERC technology (electro-reduction of carbon dioxide) shall be tested. In an electrochemical reactor CO_2 is transferred to formates or formic acid which is a useful chemical. In the process oxygen is co-generated which also could be marketed [MAN-12].

4.6 Summary and conclusion

Different technologies can fulfill the task of carbon capture, but only two seem feasible in the cement clinker production, the post-combustion capture as an end-of-pipe solution and the oxyfuel process as an integrated technology.

Post-combustion technology has been the subject of research and has been proven in some industries in the past few years. Although some of these results could be transferred to the application in the cement industry, some issues, especially concerning the typical cement plant’s flue gas composition, still need to be proven in pilot scale. Research activities are currently on-going in the field of post-combustion capture, which includes chemical absorption, adsorption, membrane, mineralization and calcium looping technologies. The most investigated technology is the chemical absorption, which faces the challenge of a high energy demand. Developments in calcium looping or membrane processes may have a higher potential to increase the overall energy efficiency. For this reason those technologies shall be investigated in pilot plants which are currently initiated (e.g. Brevik, Taiwan Cement, Skyonic projects). Additionally, the already high level of knowledge for the post-combustion technology is discussed here as capture method for the short term implementation.

The oxyfuel technology is still at a basic research status, because the integration of the technology requires substantial adaptation of the process. Different research studies focused on several topics around the application of oxyfuel to the cement clinker burning process have been initiated in recent years. Combining these findings, the basis for further detailing is presented. Detailed R&D is still needed before this technology can advance to pilot-scale, which is the next logical step. However, currently no pilot plants are planned or initiated using the oxyfuel technology in the cement clinker burning process. As a pre-stage, ECRA is presently preparing a concept study for an oxyfuel pilot cement kiln. Due to the challenges involved with integration and the influences on the process and the material, a commercial application is not expected before 2030.

Hybrid technologies in terms of a combination of oxygen enrichment and post-combustion technologies have not been actively investigated. The benefit of those combinations depends on several factors principally concerning the energy demand, where increased demand vs. capture efficiency trade-offs are the key decisions for the multiple combinations. Therefore, the data basis is too low to make reliable statements on technical and economic barriers and potentials.

In summary, the cement industry, its supplier industry network and universities have studied different capture technologies during recent years but further studies and pilot tests are required to improve and accelerate the knowledge gathering.

5 Technical and economic barriers of CCS in the cement industry

5.1 Reference scenario and boundary conditions

5.1.1 Calculation basis for the economic analysis

Table 5-1 Economic boundaries of the cost estimation

Parameter	Assumption
Location	Europe
Currency	Euro
Economic plant life	25 years
Production capacity	– 1.36 M t cement per y – 80% capacity rate
Capital charges	– Discount rate 8% – No inflation
Contingencies/ fees	10% of installed costs
Taxation/ Insurance	1% of installed costs per year
Labour	– Annual salary operating labour 60,000 €/person/year – Administrative/ support 30% of operating/maintenance labour – 320 days of operation – 5 shifts – Maintenance labour included within labour costs
Maintenance costs	5.0 €/t cement
Miscellaneous materials	Unexpected materials needed apart from usual operation
Emission trading	No CO_2 emission costs
Fuels	– coal: 80 €/t – alternative fuels: 15 – 25 €/t (average 20 €/t)
Raw materials	Limestone, iron oxide, sand etc. 5.0 €/t clinker
Power	80 €/MWh
Process water	0.2 €/m^3
TPC	170 M €
Installed costs	48% equipment costs + 37% civil and steel work + 15% erection
Average heat value, coal	26,000 kJ/kg
Average heat value, alt. fuels	18,000 kJ/kg

Production costs were estimated for the described reference plant based on ECRA's expertise, the assessment of external industry experts and published values on the basis of 2013 cost values. The total plant costs (TPC) are in line with the costs as given in [CSI-09]. They do not include cost for land property (in particular the restoration of the quarry), cost for emerging emission abatement measures (e.g. SCR) and other associated costs (e.g. permits, allotment etc.). The equipment costs can vary due to different designs, suppliers and local specifications and are therefore subject to an uncertainty of ± 35%. In addition to the total plant costs, owner's costs and interest during construction determine the total capital required (TCR). They are used to calculate an annual capital charge based on the annuity calculation, as follows:

$$K = A_0 \times \frac{i \times (i+1)^n}{(1+i)^n - 1}$$

K: annual capital charge
i: discount rate
n: life time years
A_0: investment costs

The estimation of variable operating costs depends on consumables such as material input, energy demand (thermal and electrical) as well as fuel type and miscellaneous consumable materials. Variable operating costs are determined based on the input parameters of the reference plant as provided in section 1.3. Fixed operating costs are defined by operational and administrative labor, maintenance, taxes and insurance costs. The economic boundaries for the installation and operation of the cement plant for this analysis are partly given by IEAGHG and relate to location, economic plant life and several other factors, which influence the operational and the capital costs (see **Table 5-1**). Carbon Dioxide emission costs from emission trading systems like EU ETS are unpredictable and therefore neglected in the calculation. In general carbon capture technologies become economic feasible if CO_2 prices by tax/trading are higher than avoidance costs.

Table 5-2 Sensitivity of operational costs for worldwide regions, Source: [McK-08, IEA-08]

	Europe	**Middle East**	**China**
Coal costs	65 – 100 €/t	60 – 80 €/t	40 – 55 €/t
Natural gas costs	6 – 8 €/GJ	2.5 - 3 €/GJ	3 -5 €/GJ
Electricity costs	80 €/MWh	25 – 35 €/MWh	60 €/MWh
Labour costs	60,000 €/person, year	5 -15,000 €/person, year	5 -10,000 €/person, year
Employees per plant	100	300	150
Total plant costs	170 €/t yearly production capacity	70 – 85 €/t yearly production capacity	70 €/t yearly production capacity
Raw material costs	5 €/t clinker	1.5 €/t clinker	1.5 €/t clinker
Maintenance	5.0 €/t cement	2.5 €/t cement	2.5 €/t cement
Annual capacity	1 M t clinker	3 M t clinker (thermal energy 3,020 kJ/kg clinker)	2 M t clinker (thermal energy 3,180 kJ/kg clinker)

Due to the variability of parameters a sensitivity analysis of the costs based on the following parameters is given for each scenario:

- Sensitivity to a world regions in terms of material, labour and investment costs (compare **Table 5-2**)
- Sensitivity to fuel costs and electricty prices
- Sensitivity to plant life (40 years)

5.1.2 Economic assessment of the reference plant

The reference cement plant used for this study is defined as a conventional green-field cement plant, whose cost estimation is given below. The technology of the conventional cement plant is proven and therefore not subject to a learning phase. The production costs as given in **Table 5-7** sum up from:

- Capital costs based on the identification of equipment expenditure (**Table 5-3**) and resulting total capital required (**Table 5-4**)
- Variable operating costs (**Table 5-5**)
- Fixed operating costs (**Table 5-6**)

Table 5-3 Reference scenario: Equipment costs

Aggregate	Costs in M €	in % of total
Raw material preparation		
Crushing plant	3.5	5%
Storage, conveying raw material	3.5	5%
Raw meal preparation		
Grinding plant, raw meal	16.8	24%
Storage, conveyor, silo	2.1	3%
Clinker production		
Kiln plant	11.9	17%
Cement production		
Grinding plant, clinker	9.8	14%
Silo	9.8	14%
Packaging and loading		
Packaging plant, conveyor, loading, storing	6.3	9%
Coal grinding		
Mill, silo	6.3	9%

Table 5-4 Reference scenario: Total capital required

Capital costs, reference case	**Investment costs in M €**
Equipment costs	70.0
Civil, Steelworks, Erection Others	75.5
Installed costs	145.5
EPCC	10.0
Contingency, fees	14.5
Total plant costs (TPC)*	170.0*
Owners costs	11.9
Others (working capital, start-ups, spare parts)	8.0
Interest during construction	6.4
Total capital required (TCR)	196.3

* Excluding land property (in particular the quarry), emerging emission abatement technology (e.g. SCR) and developing cost (power and water supply)

Table 5-5 Reference scenario: Variable operating costs

Item	**Reference case**
Raw materials	3.7 €/t cement
Fossil fuel	5.2 €/t cement
Alternative fuel	1.0 €/t cement
Power, kiln plant + grinding	8.8 €/t cement
Process water	0.014 €/t cement
Misc.	0.8 €/t cement
Total variable operating costs	19.5 €/t cement

Table 5-6 Reference scenario: Fixed operating costs

Item	**Reference case**
Maintenance	5.0 €/t cement
Operational labour	5.5 €/t cement
Administration/ support	2.3 €/t cement
Insurance costs	0.8 €/t cement
Local taxes	0.8 €/t cement
Total fixed operating costs	14.4 €/t cement

Table 5-7 Reference scenario: production costs

Item	
Capital charges	17.0 €/t cement
Fixed operating costs	14.4 €/t cement
Variable operating costs	19.5 €/t cement
Production costs	50.9 €/t cement* (45 – 55 €/t cement)

* Excl. freight, raw material deposit, land property, permits etc.
The range of production costs is based on different utilisation rates from 70 to 90%

These production costs exclude the costs for the raw material deposit (restoration), land property, permits etc. Also excluded are freight costs for cement delivery (typically between 15 and 20 €/t_{cement}). However, production costs of 50.9 €/t_{cement} are taken as the basis for the following evaluation of capture costs, since the additional costs are not affected by CO_2 capture and are hard to determine due to the high uncertainty of influencing parameters.

The impact of the different regions on operating costs is shown in **Figure 5-1** and **Figure 5-2**. In principle the variable operating costs are lower due to the lower price level of consumables and energy. But costs related to fossil fuels especially in Middle Eastern region are comparable high since the coal substitution rate by alternative fuels is additionally lower. The fixed operation costs are subject to the lower labour costs in non-European countries, which have a significant influence on the total production costs. In the baseline scenario a sensitivity analysis results in a decrease of the production cost of 44.6% in the Middle Eastern and of 53.3% in the Chinese regions (compare **Figure 5-3**).

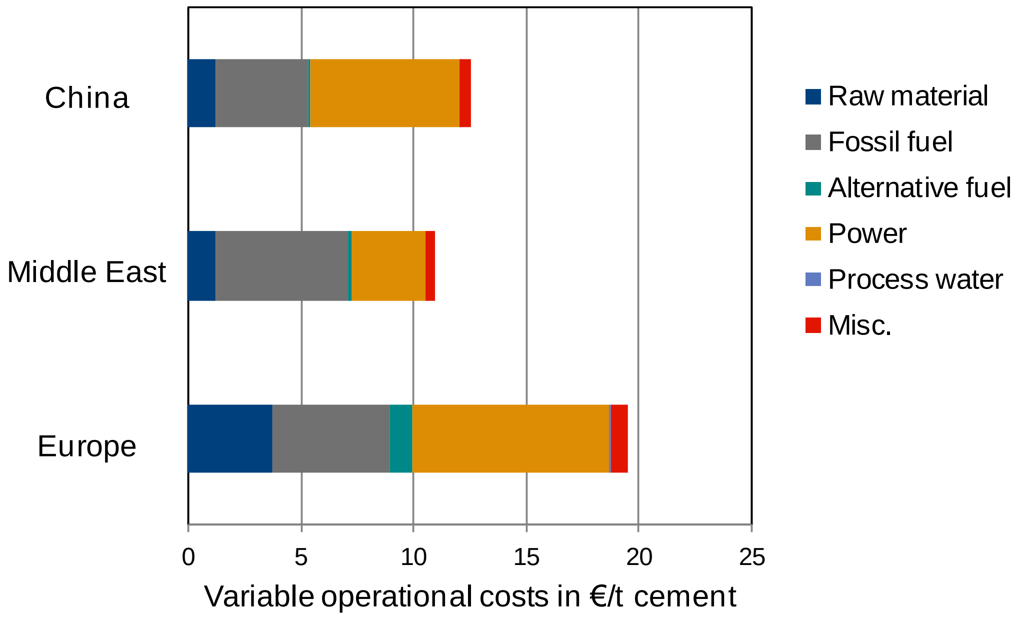

Figure 5-1 Sensitivity of variable operating costs for Non-European regions

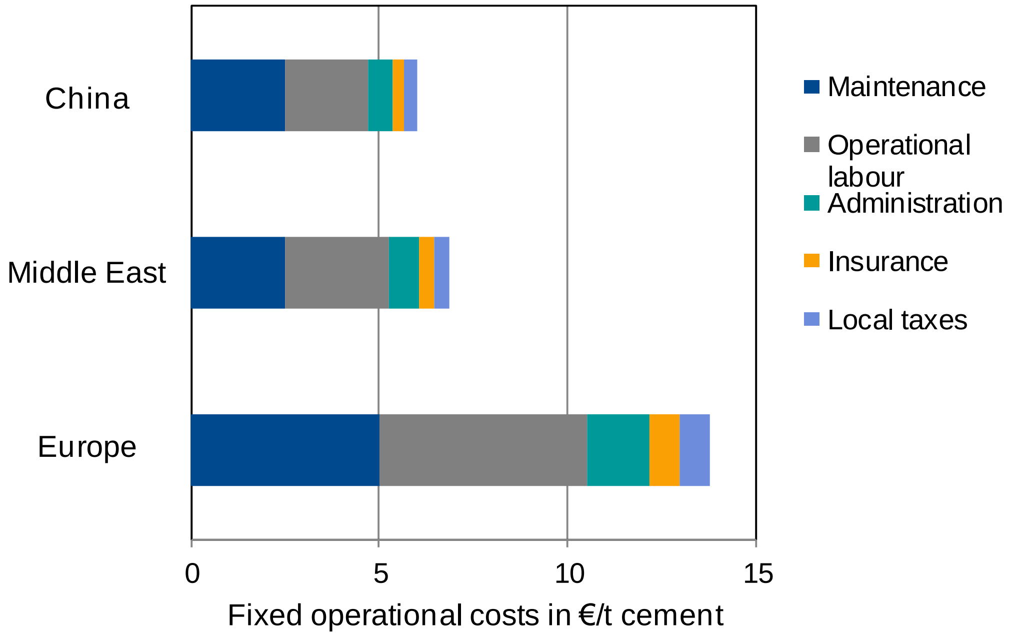

Figure 5-2 Sensitivity of fixed operating costs for Non-European regions

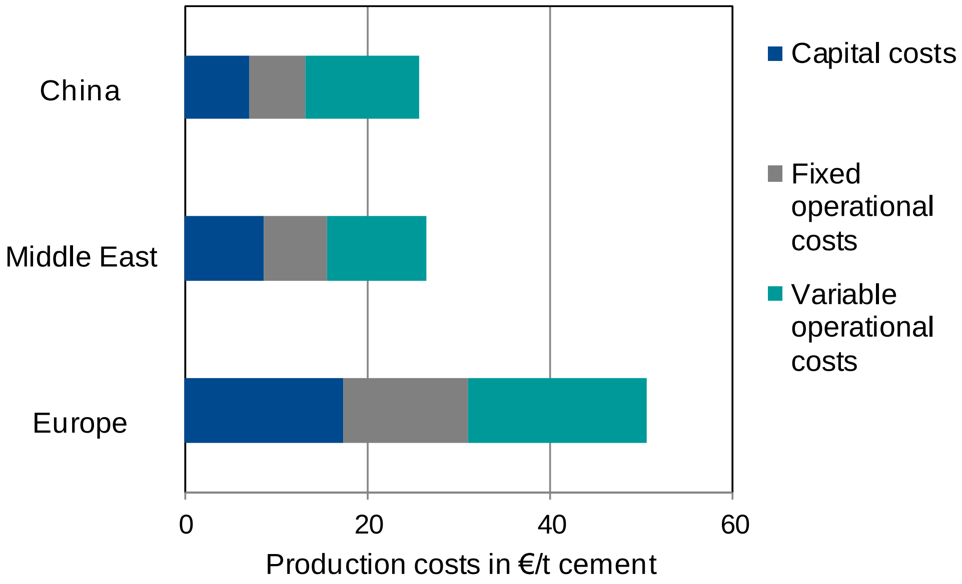

Figure 5-3 Sensitivity of production costs for Non-European regions

The operating costs are the main influencing factor on the production costs. The sensitivity of operating costs to energy and raw material price fluctuation is illustrated in **Figure 5-4**. The influence of price fluctuation of alternative fuels and raw materials are low, as the costs are relatively low at the moment and the fraction of alternative fuels remains low. Higher influence can be observed for primary energy sources like coal and power. Against this background the expected increase of electricity costs will gain in importance in the next years due to higher fraction of renewable power production and CO_2 trading.

The capital costs are strongly influenced by the economic plant life. In the cement industry a plant life of 40 years is common. Taking this time interval as a basis for the estimation of capital costs, the annual capital charges for the reference case are reduced to 15.2 €/t cement, meaning a reduction of ca. 10% of capital charges and 3.5% of production costs.

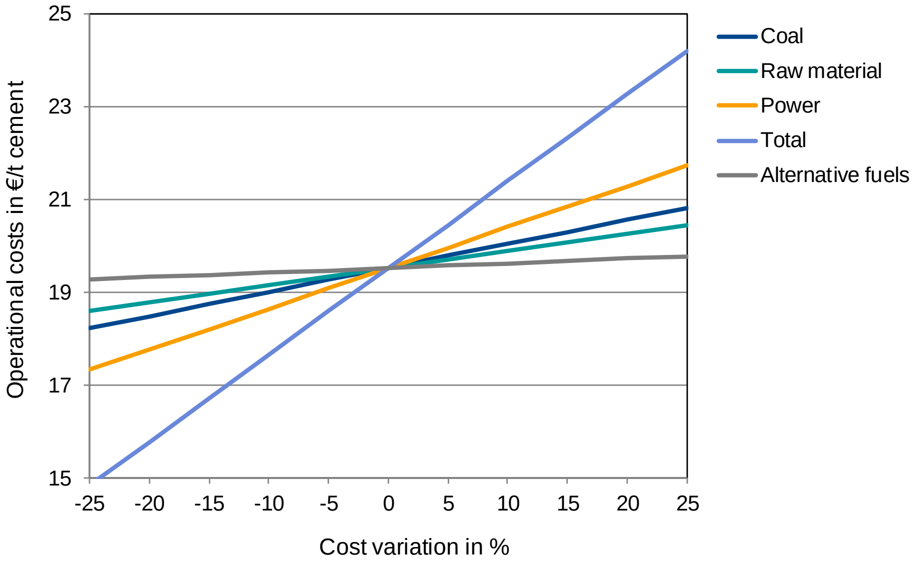

Figure 5-4 Sensitivity to energy and raw material prices in Europe

In summary the named values are only valid for the described reference plant, as many costing parameters are related to site specific boundary conditions (e.g. quarry and raw material, type of kiln plant, availability of alternative fuels and their composition).

5.1.3 Calculation methods for CCS costs

As the basis for the technical and economic evaluation some boundary conditions are defined. For the technical analysis of the different technologies certain requirements are fixed in order to compare them on the same basis. The efficiency of the capture method is rated by the capture rate, which is set to 90%. Moreover the purity of the resulting CO_2 stream influences significantly the energy demand of the capture method. For this reason the purity limitations of the CO_2 are specified in **Table 5-8**.

Table 5-8 CO_2 purity requirement of transport system based on specifications of IEAGHG

CO_2 maximum impurities for pipelines (vol. basis)	
H_2O	50 ppm
N_2 /Ar	4%
O_2	100 ppm
CO	0.2%
CH_4 and other hydrocarbons	4%
H_2S	20 ppm
SO_2	100 ppm
NO_x	100 ppm
Total non-condensables	4%

As the regulatory framework of the purity requirements is still under discussion, a reasonable purity is assumed, which does not impair the transport system by corrosion or avoids the formation of a second liquid phase. Pipeline transportation is assumed which in turn defines the CO_2 phase conditions of 11 MPa pressure and maximum temperatures of 30°C.

The costs for CO_2 emission avoidance can be calculated in comparison to these reference scenario production costs. Two cases are differentiated:

- CO_2 avoidance costs (direct emissions only): Calculation is based on of reduction direct emissions, as follows

$$C_{avoided\ (direct)} = \frac{PC_{CCS} - PC_{Base}}{E_{Base} - E_{CCS}}$$

C: cost of avoided emissions
PC: production costs
E: CO_2 emissions

The calculation includes the reduction of CO_2 emissions related to the reference case, which are generated on site by combustion and material decomposition. Since cement producers are charged for their direct emissions, this value provides the industry information about the economic feasibility of capture methods in comparison to CO_2 prices like the EU Emissions Trading System EU Allowances (EUAs). This calculation assumes that post-combustion capture would not be allowed without capturing the CO_2 emissions from the steam generation.

- CO_2 avoidance costs (incl. indirect emissions): Calculation is based on the reduction of direct and indirect emissions, as follows

$$C_{avoided\ (indirect)} = \frac{PC_{CCS} - PC_{Base}}{E_{Base} - E_{CCS} - E_{power} + E_{Generated}}$$

The calculation includes the fact that additional power generation is needed from the grid for the capture plants causing the release of indirect CO_2 emissions to the environment, which are not produced in conventional cases. In case of post-combustion capture the surplus of generated power to the grid is positively charged. **Table 5-9** provides the calculation basis for imported and exported power in terms of prices and CO_2 emissions for the two considered power generating systems (coal and gas).

Table 5-9 Comparison of technologies for energy supply at 800 MWe capacity (information by IEAGHG)

	Pulverized coal power plant	**NGCC**
Electricity prices with CCS	92 €/MWh	73 €/MWh
CO_2 emissions with CCS	95 kg/MWh	40 kg/MWh
CO_2 emissions without CCS	757 kg/MWh	348 kg/MWh

In summary, due to the R&D status of the capture technologies in the cement industry the performance of these technologies and the projected costs to the time when CCS would be applied at large scale (2020/30) involve conjectures which create a high degree of uncertainty. For this reason the costing basis year relates to price and technology level of the current year 2013. Furthermore the identified costs of the capture technologies are based on a first of a kind plant which costs might be higher than next generations due to learning curves and technology improvements.

5.2 Post Combustion Technology

5.2.1 Technical barriers

Post-combustion CO_2 capture measures are end-of-pipe technologies which should not affect the production process at all. However, there are some technical requirements regarding the integration into the clinker burning process which could affect the applicability of post combustion measures. Chemical absorption is the most mature technology as there are operational experiences available from different industrial sectors. In contrast to this, membrane, adsorption, mineralisation technologies are in an early stage of development and many technical barriers for potential implementation have not been fully identified. Therefore, the following assessment is focussing on absorption technologies, especially on amine scrubbing.

5.2.1.1 Integration of the technology in the cement plant/ Synergies to power production

Flue gas composition and temperature:

The composition of the flue gas affects the operation of the capture process. The concentration of acid components such as SO_2 and NO_2 are critical for the degradation of the absorbents and trace elements may lead to catalytic decomposition of the sorbents.

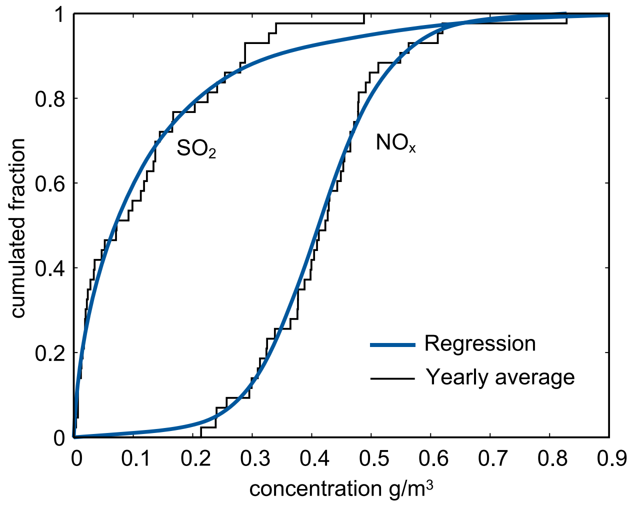

Figure 5-5 Distribution of SO_x and NO_x in cement kiln flue gases (based on Germany) [ECR-09]

An evaluation of all German cement kilns showed that the average NO_x-concentration is quite evenly distributed around 410 mg/m^3.The distribution of SO_2 emissions shows that most plants emit very little SO_2 (> 50% below 100 mg/m^3), moreover the SO_2 emissions of the cement plant are strongly dependent on the quarry and are therefore site specific. This evaluation takes only the German cement kilns into account, it can be expected that the general distribution characteristics do not differ significantly from other countries while the distribution parameters may change (**Figure 5-5**). Therefore, the application of chemical absorption processes can require the installation of additional secondary emission abatement technologies.

In addition to harming pollution in the gas phase, flue gases from cement kilns contain dust, which could also cause degradation. Although filter could reduce the dust content to less than 10 mg/m^3 these substances has to be considered concerning an adequate solvent selection.

The chemical absorption process for CO_2 capture is carried out at temperatures between 40 and 60°C (or even lower). In some cases, a cooling system would be required to cool down the flue gas to the appropriate temperature. In contrast to this, calcium looping is a high temperature process, so that flue gas from the preheater tower could be directed to the carbonator of the calcium looping system.

Space requirements:

In some cement plants there is almost no room for major additional technical installations like absorber and desorber columns, carbonators and calciners, CO_2 processing units, etc. Therefore, the construction area of a carbon capture installation can be a limiting factor for conducting a project. In some cases, also additional flue gas treatment may be required like SCR for NO_x reduction or wet scrubbers for SO_2 reduction. Therefore, the retrofit of post-combustion technologies could be limited by the space requirements of the additional installations both for CO_2 capture and for flue gas treatment.

Waste heat recovery:

Chemical absorption processes, especially amine scrubbing, exhibit a high energy demand for the solvent regeneration. Waste heat from the clinker burning process should be utilized to regenerate the solvent. Available waste heat from a 3,000 t/d BAT plant (5 cyclone stages) could be composes as follows:

- Preheater exit gas: 22 MW (wheras only 70% is usable heat above 100°C)
- Cooler exhaust air: 13.6 MW
- Wall losses (about 60% from the rotary kiln): 10.6 MW

However, the waste heat potential depends on the individual kiln system. In conventional operation waste heat from flue gas is used for raw material drying, thus the degree of available heat for the capture plant is depending on site specific boundaries like the raw material moisture. The recovery of the other large heat source, the wall radiation is not proven. Even if the total available and usable heat (without wall heat) is utilized for the capture plant only 15 to 30% of the required energy for the solvent regeneration (depending on solvent type) could be covered under the named heat sources. The available waste heat could be further increased by decreasing the preheater cyclone stages which increases the thermal energy demand of the clinker burning process. These comparatively small improvements make a medium sized CHP power plant necessary to provide the low pressure steam for the solvent regeneration.

Health and Safety issues:

The use of chemical absorption technologies requires consideration of health and safety issues. A safety plan for the handling of the absorbent solutions and / or hazardous waste steams has to be established so that any potential adverse effects on the health of the plant personnel and the environment are eliminated.

Environmental and Nuisance issues:

With regard to amine scrubbing technologies the emissions of amine or even nitrosamines into the atmosphere require consideration because of their potential environmental and nuisance impact from odour. These issues could be minimized by suitable cleaning technologies like extra scrubbers at the top of the CO_2 absorber column. It has to be ensured that only insignificant concentrations of the chemical absorption compounds are emitted into the atmosphere.

Waste solvents / waste sorbents:

Degraded solvents from chemical absorption processes have to be discharged from the cycle. Depending on the type of solvent, a make-up rate of 1 - 3 kg/t CO_2 could be needed which would correspond to 1,400 to 4,100 tonnes/year of additional waste for the reference cement plant to dispose of or use. A utilization of the waste (amine containing) solvents in the clinker burning process could be possible, e.g. as reducing agent for the SNCR process.

Deactivated sorbents from the calcium looping process could be utilized in the clinker burning process as alternative raw material. Corresponding research with waste sorbents from power plants has already been carried out with the result that up to 30% of raw meal could be substituted by these sorbents [AiF-13].

Synergies to power production:

The application of chemical absorption technologies at the clinker burning process requires low pressure steam for solvent regeneration which could be provided by an additional on-site power plant. In addition to the steam production, the power plant could cover the electrical energy demand of the cement plant or generate a surplus of energy which could be used for CO_2 compression or fed into the grid. The production of additional electrical energy is considered in the cost calculations in the following chapter.

Also other synergies could be exploited between power generation and cement production. For example, the calcium looping process could be applied at a power plant – resulting in a significant CO_2 reduction at moderate costs and a low energy penalty (< 3% points without CO_2 compression). The deactivated sorbent (purge) from the calcium looping process could be reused in the clinker burning process as alternative raw material. An optimum is achieved if the power plant and the cement plant could work as integrated plants which would also reduce transport costs for the large mass of sorbent. The utilization of the (partly) calcined sorbent would lead to lower CO_2 emissions and a lower energy demand of the clinker burning process. Furthermore, when using the calcium looping process, no additional emission abatement measures ($DeSO_x$, $DeNO_x$) would have to be installed, resulting in lower investment and operating costs. Initial investigations about this concept for CO_2 reduction and the alliance between power and cement production have been carried out recently [AiF-13], [ROM,-11], [DEA-11], [ROA-13]. However, the utilization rate of the calcined sorbent in an existing kiln system (state-of-the-art technology) would be limited due to technical reasons.

An extensive input of decarbonated material would lead to significant changes in the clinker burning process due to redistribution of fuel from the precalciner to the main burner and due to reduced CO_2 volume flows, which would impair the preheater function.

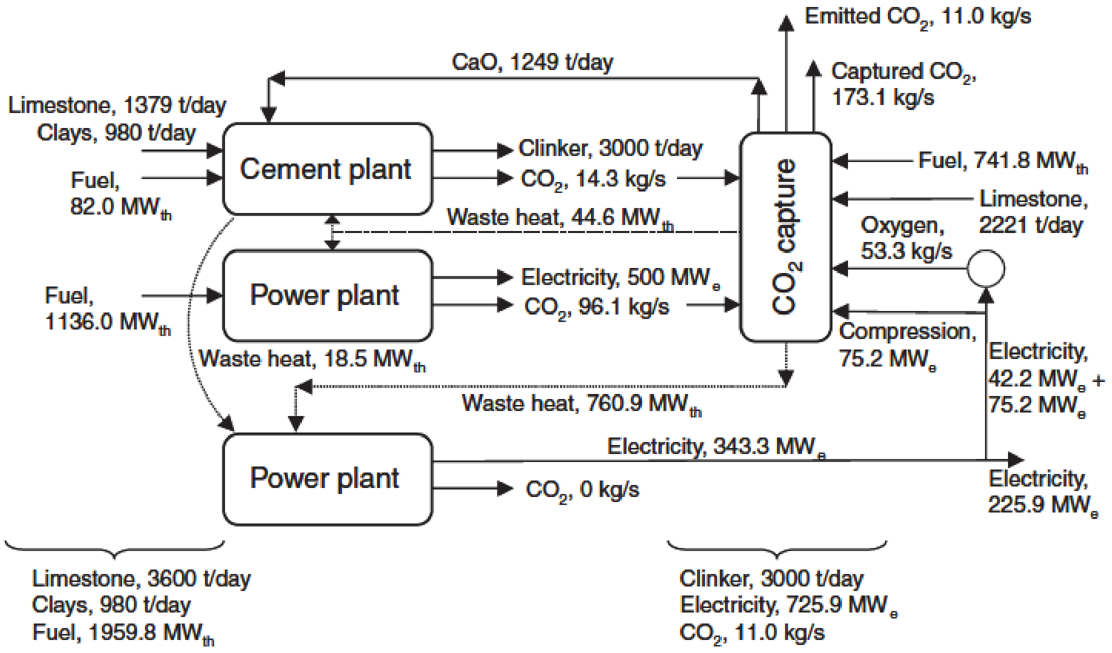

Figure 4-5 Symbiosis between cement and power plants with a joint CO_2 capture plant [ROM-11]

Other plant configurations could offer synergies between power and cement plants. A collective treatment (calcium looping process) of the cement kiln's and power plant's flue gas (see **Figure 4-5**) would enable significant cost reductions for the overall capture installation (12.4 €/t CO_2, 94% avoided CO_2 emissions) [ROM-11].

5.2.1.2 Energy demand

The application of amine scrubbing technology at the clinker burning process would manifest synergies to a power plant, as the regeneration of the CO_2 rich sorbent requires low-pressure steam. The clinker burning process does not provide enough waste heat for a sufficient steam production to carry out the sorbent regeneration. It has been estimated [AiF-12] that not more than 15% of the required reboiler energy could be extracted from the clinker burning process on the basis of an amine scrubbing process (using MEA solution of 4 GJ/t CO_2). Therefore, an additional power plant would be needed (which would entail additional CO_2 emissions). A rotary cement kiln with a clinker capacity of 3,000 t/d with a specific emission of 0.8 kg CO_2/kg clinker would need a steam generator to supply the required steam for the solvent regeneration. In the case of a coal operated combined heat and power production (CHP), where CO_2 emissions are simultaneously captured in the absorber, some 150 MW_{th} would be needed for the MEA solution or in the case of an improved solvent regeneration at a surplus of power production. By implementing a natural gas combined cycle (NGCC) less CO_2 emissions are generated from power production, which reduces the reboiler duty and therefore the additional energy demand. Apart from MEA sorbent different solvents are already commercially used at an energy demand of the desorber in the region of 2.6 to 3.0 GJ/t CO_2 [END-10] in case of coal or gas fired boiler for power production. Flue gases from the cement kiln usually contain 15 to 30 vol.% of CO_2, which may result in lower energy demand for generation due to the improved absorption at higher CO_2 concentrations but this still needs to be proven.

The best solution may be if the energy demand could be satisfied by an existing nearby power plant, provided the plant could be easily modified to extract low pressure steam from its turbine. In this situation a collective treatment of the cement kiln's and power plant's flue gas would be advisable.

The application of other post-combustion technologies (calcium looping, adsorption, membranes) would not necessarily require an investment for a steam production facility.

5.2.1.3 R&D status and needs

Based on the above consideration some issues could require further investigation:

- New solvents, which require lower energy demand for regeneration
- Alternative technologies apart from amine scrubbing like calcium looping or membranes
- Further integration of the capture plant with waste heat recovery
- Investigations on waste solvent disposal to a cement kiln with regard to the clinker chemistry and the process operation

From a technical point of view, as an end-of-pipe technology some of the experience of the power sector can be transferred to the post-combustion capture from cement plants. A few pilot plants have currently been initiated from which results are expected in the forthcoming years. As a next step, demonstration of the post-combustion capture in the cement industry would be required at a large-scale, which from a technical point of view could not be expected before 2020. Only after 2020 could widespread deployment occur. However, from an economic point of view, the time frame will to a large degree depend on substantial funding, availability of storage sites, the legal framework and on public acceptance.

5.2.1.4 Technology providers

The state of development of carbon capture technologies is different - some technologies are still on a research level, whereas other technologies have been tested in small-scale and pilot projects (e.g. in the power sector) so that they can be regarded as state-of-the-art. Technologies, which are still on the research level, are not yet commercially available. In these cases, technology providers may offer only mobile or small-scale equipment to carry out pilot trials. On the other hand, chemical scrubbing technologies have been tested in various industrial sectors so that technology providers could also offer equipment for full-scale carbon capture plants (up to 1 Mt/y).

All in all, there are several technology providers for chemical absorption on the market, but only a few companies which are involved in the first small-scale trials with other post-combustion technologies. Examples of some of the technology providers for chemical absorption are Linde Engineering GmbH, Aker Solutions ASA, Statoil ASA, Siemens AG (Energy sector), Fluor Corporation, Cansolv Technologies Inc., Mitsubishi Heavy Industries (MHI) Ltd.

5.2.2 Cost estimation

Several studies, which were published during recent years, contain cost estimations for the application of CO_2 capture technologies at the clinker burning process. The figures for post-combustion technologies were focussing on the chemical absorption process which is the most mature technology. However, due to the lack of pilot trials at cement kilns no reliable data about the solvent degradation, the heat demand for the solvent regeneration and the need for the installation of other abatement technologies is available. As a result of this, operational experiences from other industrial sectors were used for the current cost estimations. Other post-combustion technologies (e.g. membrane technologies, adsorption technologies), which could eventually be applied at cement kilns, are in an early stage of development, so that it is not yet possible to carry out well-founded cost calculations. However, one of the objectives of the planned pilot projects is the determination of sound cost figures for the different post-combustion variants so that more data will be available in two or three years.

In the following table, the cost figures from the different studies are summarized.

Table 5-10 Cost calculations for post-combustion capture, literature

	Norcem study	**M. MacDonald study**	**Li study**
Kiln capacity (clinker production)	3,300 t/d	2,760 t/d	6,000 t/d
Carbon capture technology	Chem. Abs. / MEA	Chem. Abs. / MEA	Chem. Abs. / MEA
Additional power plant (CO_2 captured in PCC Plant)	NGCC	CHP	CHP
Flue gas pretreatment	SNCR, $DeSO_x$	SCR, $DeSO_x$	SCR, $DeSO_x$
Available waste heat for steam production	15%		
Economic plant life		25 y	25 y
Interest rate	7%	10%	14%
Load factor	84%	90%	91%
Investment costs of capture plant	110 M € [b]	294 M €	168 M € [a]
Operating costs	20 M €/y [b] [c]	31 M €/y	49 M €/y [a]
Total specific costs (CO_2 captured)	45 €/t CO_2 [b]	59 €/t CO_2	
Total specific costs (CO_2 avoided)		107 €/t CO_2	51 €/t CO_2 [a]

[a] original costs calculated in US-$ [in 2013]
[b] original costs calculated in NOK [in 2006]
[c] operating costs without cost for CO_2 delivery

In most cases, figures for operating costs (including fixed and variable costs), investment costs and total costs have been presented. The boundaries of the individual cost estimations are mentioned in connection with every study. It is clear that most of the research activities on carbon capture are aiming to reduce the costs of carbon capture measures significantly (e.g. by reducing the energy demand of solvent regeneration processes). Nevertheless, the presented figures represent the current state of development and do not predict potential future costs. Cost figures for the base case (cement production without carbon capture technologies) are included in chapter 4.1.

Within the framework of a thesis at the University of Waterloo, S.M.N. Hassan carried out a techno-economic study about CO_2 capture at cement kilns [HAS-05]. After that a technical and economic study was carried out about the feasibility of carbon capture at the Brevik cement plant in Norway [HEG-06]. In 2008 the British consultant company Mott MacDonald in cooperation with the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) carried out a study about CO_2 capture in the cement industry – including cost calculations for post-combustion capture [IEA-08], [BAR-09]. Another techno-economic study for the application of carbon capture in a Chinese cement works was carried out recently [LI-13]. The following costs figures represent the additional costs for the installation and operation of a post-combustion plant (chemical absorption), including a CHP plant for the steam production (Norcem, Mott MacDonald and Li studies). These cost studies show an enormous difference which confirms the costs dependency of the technology that is used and the sensitivity of the study boundary conditions. As such there remains uncertainty regarding the cost estimations of this technology to the cement production process.

The investment costs include the costs for the CHP plant, $DeNO_x$ and $DeSO_x$ plants, for civil works, construction, instrumentation, design, fees, contingency, owners cost, etc. Revenues from power production in the CHP plant are accounted in the calculation of the variable operating costs. Furthermore the operating costs of the $DeNO_x$ und $DeSO_x$ plants are included.

Table 5-11 Operating costs for post-combustion capture, literature

	Norcem study	**M. MacDonald study**	**Li study**
Reference region	Norway	UK	China
Kiln capacity (clinker production)	3,300 t/d	2,760 t/d	6,000 t/d
Operating costs	20.3 M €/y	31.3 M €/y	49.0 M €/y [f]
Fixed operating costs	5.0 M €/y	16.2 M €/y	9.1 M €/y
Variable operating costs	15.3 M €/y	15.1 M €/y	39.9 M €/y
Electricity costs	0.75 M €/y	- 5.1 M €/y [f]	- 2.6 M €
Fuel costs	11.6 M €/y	14.8 M €/y	31.0 M €/y
Absorbent costs (MEA)	2.5 M €/y	2.5 M €/y	6.8 M €/y
Other variable operating costs	0.4 M €/y	2.9 M €/y	4.7 M €/y

[f] Net effect due to power consumption of the post-combustion plant and power production in the CHP plant

In order to allow a direct comparison to the oxyfuel technology the CO_2 avoidance costs are calculated on the assumptions described above. The costs for operation are determined on the material and energy demand given in [IEA-08] for a process using amine scrubbing in combination with a combined heat and coal power plant (CHP). Steam required for the post-combustion solvent scrubbing could also be provided by a natural gas combined cycle plant (NGCC). The price of the respective fuel and the CO_2 emissions associated with the electricity generation for the cement production and CO_2 capture plant can differ between the technologies used for power production. For this reason a second post-combustion scenario has been considered based on the Norcem values.

The production costs (**Table 5-16**) are estimated based on the sum of:

- Capital costs on the basis of total capital required (**Table 5-13**)
- Variable operating costs (**Table 5-14**)
- Fixed operating costs (**Table 5-15**)

The additional equipment costs are related to the CO_2 capture and compression plant, steam production by either coal or NGCC CHP and to flue gas conditioning. Emissions of NO_x and SO_2 need manageable abatement techniques to meet today’s emission limits. State of the art techniques to reduce NO_x emissions are low-NO_x burner and SNCR processes (Selective Non Catalytic Reduction). SCR (Selective Non Catalytic Reduction) technologies are currently tested in some cement plants. Sulphur dioxide emissions are subject to raw material and fuel choice. As the solvent CO_2 scrubbing technologies could be impaired by those emissions additional abatement techniques may be required.

The variation of investment costs given in the above named studies indicates that there is a large uncertainty in costs due to regional aspects and development status. The Li study is related to Chinese market at regional cost indices of equipment to Europe of 0.68. Moreover capturing CO_2 by treating the flue gas from a large-scale cement plant the diameters of the adsorption columns are outside the conventional proven sizes. In the following calculation the equipment costs as given in **Table 5-12** are based on equal designs but differ in technology of power production and its resulting flue gases. The equipment costs are determined by emission abatement technologies for NO_x and SO_2 steam producing equipment (CHP or NGCC), capture plant and compression unit as well as auxiliary equipment. The equipment costs for steam production differ depending on coal or gas firing systems resulting in a more significant difference of the overall investment costs between the two described scenarios. Furthermore NO_x emissions could be mainly traced back to the clinker burning process, which allows for comparable investment costs for the reduction equipment. The flue gas from steam production, which is simultaneously treated, contributes to the overall SO_2 emission. The extent of removed sulphur dioxide depends on the technology for steam production. Similarly the capture plant itself is sized by the flue gas and its CO_2 content. As gas fired processes exhibit less sulphur dioxide and CO_2 emissions the respective equipment could be reduced in size which would in turn reduce cost. However, some of the cost data rely on the reference cases named above which do not include inflation during the past 1-5 years since their publication.

Table 5-12 Post-combustion scenario: Equipment costs

Equipment	Solvent scrubbing/ Coal CHP	Solvent Scrubbing/ NGCC
SO_2 scrubber	22.5 M €	18 M €
NO_x reduction	4.6 M €	4.6 M €
Steam production	66.2 M €	34 M €
CO_2 capture and compression unit	39.6 M €	36.8 M €
Others	0.1 M €	0.1 M €

In addition to the the equipment costs the installed costs include the civil, engineering, designing and steel work as well as the erection. After adding 10% of the installed costs for the contingency and fees, the total plant capital (TPC) can be estimated. In addition the total capital required (TCR) includes the owner's costs and others (interest during construction, working capital, spare parts, start-up costs). In the case of retrofit, the investment costs are only based on the installation of a capture plant and the CHP/NGCC i.e. it assumes a paid-off cement plant. Correspondingly the investment for a the construction a cement plant are included in case of new installation.

Table 5-13 Post combustion scenario: Investment costs

Item	Solvent scrubbing/ Coal CHP		Solvent Scrubbing/ NGCC	
	Retrofit	New installation	Retrofit	New installation
Equipment costs	133 M €	207 M €	93.5 M €	168 M €
Installed costs	277 M €	431.3 M €	194.8 M €	350 M €
Total plant costs	304.7 M €	474.4 M €	214.3 M €	385 M €
Total capital required	348.8 M €	541.0 M €	246.4 M €	439.7 M €

In contrast to the conventional operation additional chemicals such as solvents, other chemicals and process/cooling water are needed to operate the clinker production process with post-combustion capture. Power for the PC plant is produced by either the CHP or the NGCC consuming fuel as gas or coal. The variable operating costs are related to an energy production of 150 MW for each CHP and NGCC as in the reference study, because representative cost data are available. Due to the development in solvents during recent years, less energy demand for the generation could be estimated resulting in higher surplus. An average energy demand for regenerating the solvent of 2.8 GJ/t CO_2 is assumed, which is not further specified to a certain capture technology supplier. The surplus of energy, which is not needed for the steam to the reboiler, is used to generate power. Potential influences on costs reduction of the power plants sizing are compensated by selling surplus energy.

Table 5-14 Post-combustion scenario: Variable operation costs

Item	Solvent scrubbing/ Coal CHP	Solvent Scrubbing/ NGCC
Raw materials	3.7 €/t cement	3.7 €/t cement
Fuel, kiln plant	6.2 €/t cement	6.2 €/t cement
Fuel (coal or gas), Power plant*	22.0 €/t cement	44.0 €/t cement
Power, kiln plant	8.8 €/t cement	8.8 €/t cement
Power, PC Plant	16.8 €/t cement	13.5 €/t cement
Power, generated	- 30.2 €/t cement	- 57.8 €/t cement
Cooling water	0.1 €/t cement	0.1 €/t cement
Process water	0.04 €/t cement	0.04 €/t cement
Solvent	2.5 €/t cement	1.5 €/t cement
DeNOx: Ammonia	0.4 €/t cement	0.4 €/t cement
Others (Chemicals, DeSOx etc.)	1.8 €/t cement	1.8 €/t cement
Misc.	2.4 €/t cement	3.0 €/t cement
Total	34.5 €/t cement	25.2 €/t cement

* Based on a coal price of 3 €/GJ and a gas price of 6 €/GJ

As the complexity of the process rises in both cases, the costs for maintenance and operational staff is assumed to be increased by 50% compared to the base case. Insurance and local taxes rely on the installed costs (1%) and therefore differ slightly between the two scenarios.

Table 5-15 Post-combustion scenario: Fixed operation costs

Item	Solvent Scrubbing/ Coal CHP	Solvent Scrubbing/ NGCC
Maintenance	7.5 €/t cement	7.5 €/t cement
Operational labour	8.3 €/t cement	8.3 €/t cement
Administration	3.4 €/t cement	3.4 €/t cement
Insurance costs	1.9 €/t cement	1.5 €/t cement
Local taxes	1.9 €/t cement	1.5 €/t cement
Total	23.0 €/t cement	22.2 €/t cement

Comparing the production costs of both systems, the combination with an NGCC steam production is more economic (compare **Table 5-16**). Nevertheless, in both cases the production costs are increased by 67 to 100%. For the determination of the CO_2 avoidance costs (excluding transport and storage) a capture rate of 90% has been assumed. Based on the additional CO_2 generation by the steam/power production, the CO_2 emission input for capture is 1.28 t CO_2 /t cement in case of CHP and 0.92 t CO_2 /t cement in case of NGCC. The release from the capture plant to the environment is therefore higher than related to capturing 90 %

CO_2 generated from the cement kiln solely. The net avoidance costs excluding the credit for emissions avoided resulting from surplus power exported to the grid are related to avoided CO_2 emissions of 0.48 t CO_2 /t cement in case of CHP and 0.52 t CO_2 /t cement in case of NGCC. Including the credit for surplus power exported to the grid, the emissions avoided are 0.52 t CO_2 /t cement in case of coal CHP and 0.66 t CO_2 /t cement in case of NGCC.

Table 5-16 Post-combustion scenario: Production costs and CO_2 avoidance costs

Item	**Solvent Scrubbing/ Coal CHP**		**Solvent Scrubbing/ NGCC**	
	Retrofit*	New installation	Retrofit*	New installation
Investment costs	348.8 M €	541.0 M €	246.4 M €	439.7 M €
Capital costs	30.2 €/t cem*	46.9 €/t cem	21.3 €/t cem*	38.1 €/t cem
Fixed operating costs	23.0 €/t cem		22.2 €/t cem	
Variable operating costs	34.5 €/t cem		25.2 €/t cem	
Production costs****	87.7 €/t cem*	104.4 €/t cem	68.7 €/t cem*	85.5 €/t cem
Increase of production costs		105%		68%
CO_2 avoidance costs (direct emissions)**	112.1 €/t CO_2	111.5 €/t CO_2	66.9 €/t CO_2	66.5 €/t CO_2
CO_2 avoidance costs (indirect emissions)***	103.5 €/t CO_2	102.9 €/t CO_2	52.7 €/t CO_2	52.4 €/t CO_2

*Assumption: Existing cement plant is already paid off
** Excl. transport and storage, indirect CO_2 emissions
*** Excl. transport and storage, including power emissions from grid
**** Excl. freight, raw material deposit, land property, permits etc.

A sensitivity analysis for the CO_2 avoidance costs has been calculated for the non-European market (**Figure 5-6** and **Figure 5-7**), economic plant life (**Table 5-17**) and fluctuation of energy and material prices (**Figure 5-8** and **Figure 5-9**) using the assumptions made in section 5.1.1.

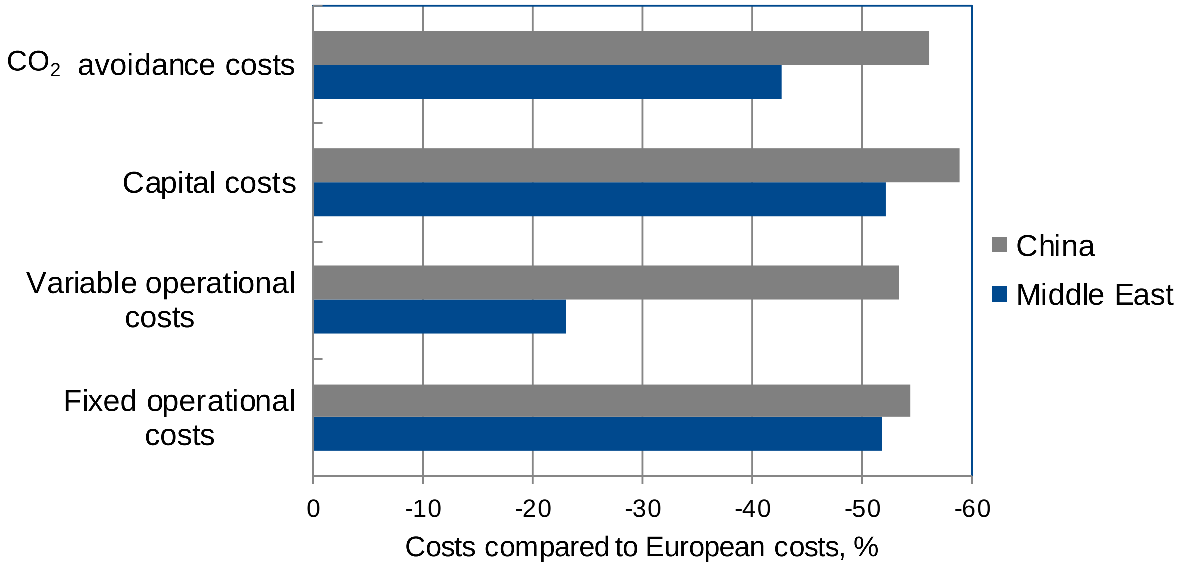

Figure 5-6 Sensitivity to Non-European markets, Amine Scrubbing with coal CHP energy supply

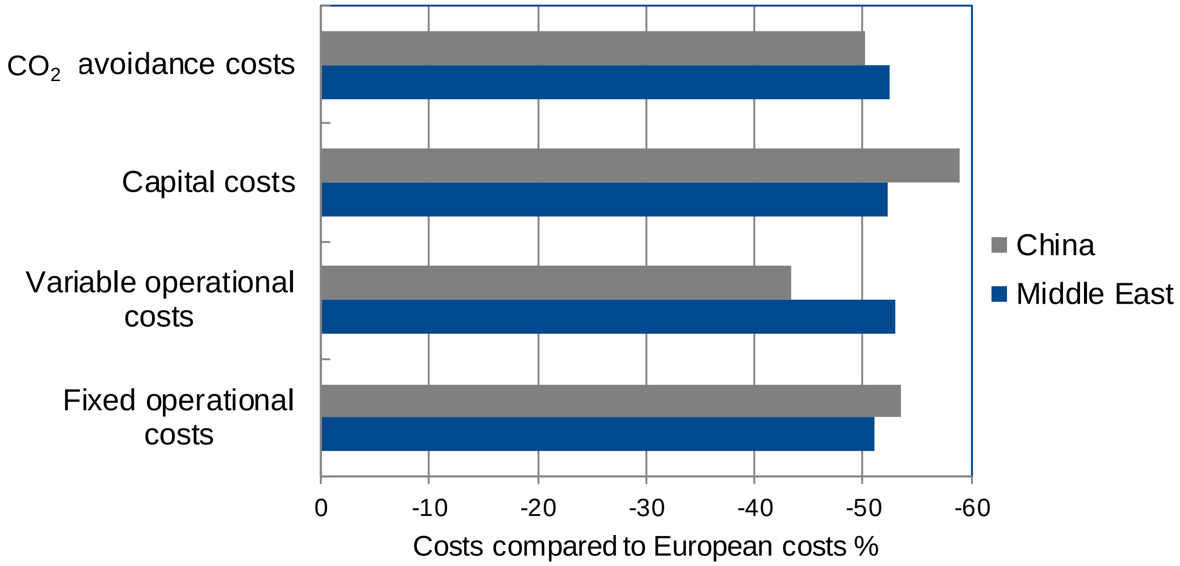

Figure 5-7 Sensitivity to Non-European markets, Amine Scrubbing with NGCC energy supply

The sensitivity to markets outside the European Union, specifically for the regions Middle East and China, results in a decrease of production costs of average 40 – 60% for both concepts. In Chinese markets the capital costs are more decisive, while the variable costs are higher compared to Middle Eastern markets. Comparing both concepts for the Middle East region, huge differences have been identified in the variable operating costs concerning the fuel that is used for the energy supply system (22% cost reduction using coal, 52% cost reduction using gas). As coal prices in the Middle East are comparable to the European price level and natural gas is cheaper in this region of the world, much higher cost reduction can be achieved using natural gas as the energy source.

Table 5-17 Post-combustion scenario: Sensitivity to economic plant life of 40 years (related to new installation)

Item	**Solvent Scrubbing/ Coal CHP**	**Solvent Scrubbing/ NGCC**
Capital costs (40 y)	41.9 €/t cement	34.0 €/t cement
Production costs (40 y)	99.4 €/t cement	81.4 €/t cement
Decrease of production costs compared to 25 y plant life	4.8%	4.8%
CO_2 avoidance costs (direct emissions)* (40 y)	101.0 €/t CO_2	58.7 €/t CO_2
CO_2 avoidance costs (indirect emissions)** (40 y)	93.3 €/t CO_2	46.2 €/t CO_2

* Excluding transport and storage, indirect CO_2 emissions
** Excluding transport and storage, including power emissions from grid

Cement plants are usually operated for a plant life of more than 40 years. The production costs, by means of annual capital charges, are decreased (**Table 5-17**) when assuming the 40 year payback. Due to the higher dependency of production costs from capital charges the

PC plant in combination with coal CHP energy supply obtains a higher cost difference. However, the avoidance costs are still lower combining the process with NGCC energy supply.

In the final step, the sensitivity of operating costs to price fluctuations has been investigated. **Figure 5-8** and **Figure 5-9** illustrate the development of operating costs with varying the energy and material prices in a range between -25% and + 25%.

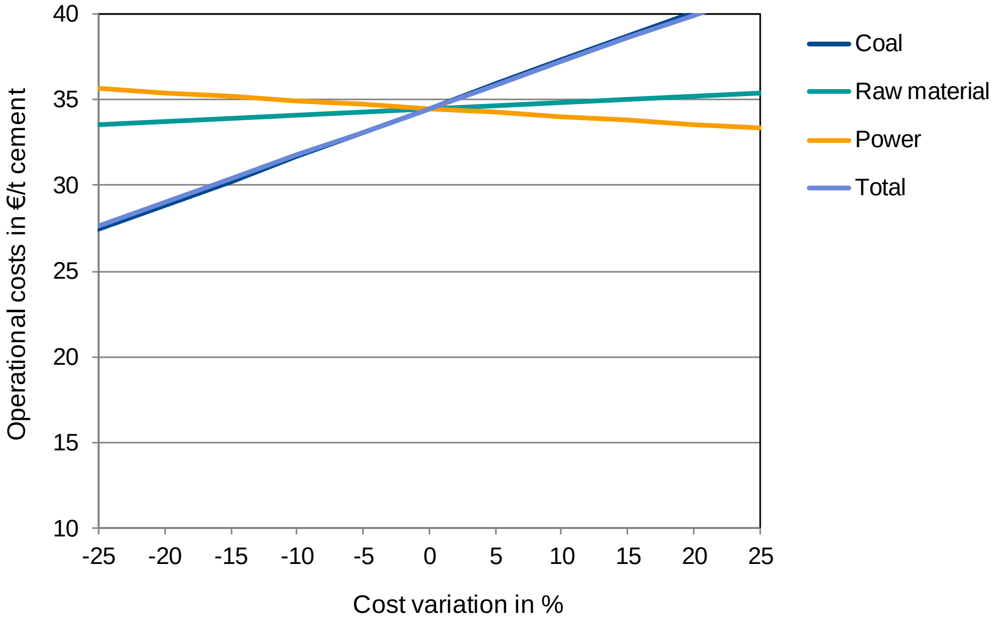

Figure 5-8 Post-Combustion scenario, CHP: Sensitivity to variable operational cost fluctuation

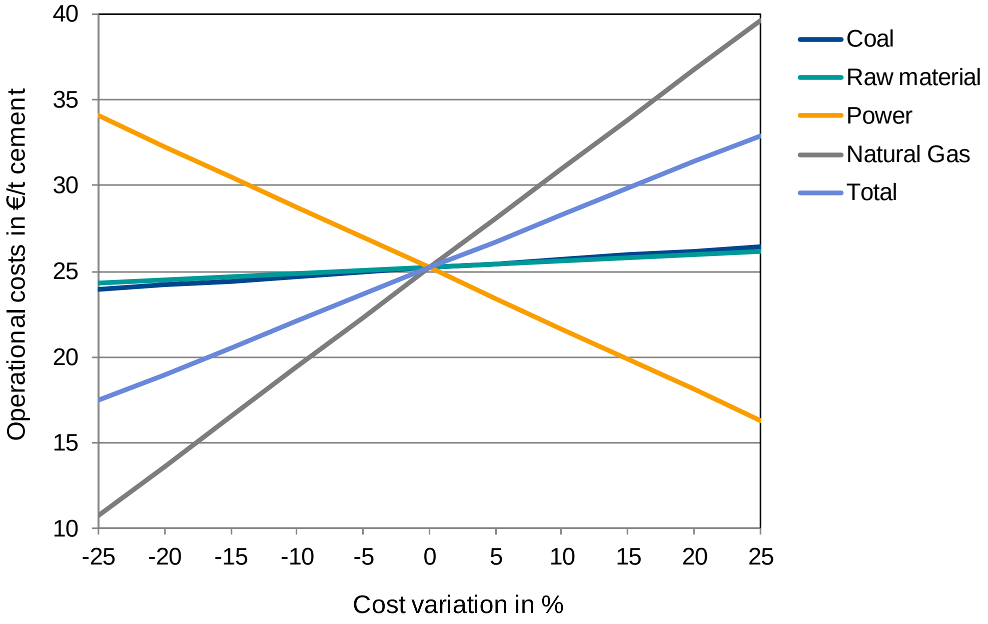

Figure 5-9 Post-Combustion scenario, NGCC: Sensitivity to variable operational cost fluctuation

Combining a post-combustion equipped cement plant with coal CHP energy supply the coal prices are the most influential parameter on the total variable operating costs. As even more power is generated by the CHP than used, the power price has reverse influence. When power prices are lower the operating costs rise due to the lower return of the surplus energy. When integrating an NGCC process, coal prices have less effect on the operating costs because the main cost driver is natural gas. Additionally, sales of the surplus power, which can be higher than in the coal CHP case, causes greater variation.

Table 5-18 Post-combustion scenario: Sensitivity to variable operating costs (related to new installation)

Item	**Solvent Scrubbing/ Coal CHP**		**Solvent Scrubbing/ NGCC**	
	- 25%	+ 25%	- 25%	+ 25%
Variable operating costs	27.7 €/t cem	41.3 €/t cem	17.5 €/t cem	33.0 €/t cem
Production costs	97.6 €/t cem	111.2 €/t cem	77.8 €/t cem	93.3 €/t cem
Difference of production costs	- 6.5%	+ 6.5%	- 9.1%	+ 9.1%
CO_2 avoidance costs (direct emissions)*	97.3 €/t CO_2	125.6 €/t CO_2	51.7 €/t CO_2	81.5 €/t CO_2
CO_2 avoidance costs (indirect emissions)**	89.8 €/t CO_2	116.0 €/t CO_2	40.8 €/t CO_2	64.2 €/t CO_2

* Excluding transport and storage, indirect CO_2 emissions
** Excluding transport and storage, including power emissions from grid

5.3 Oxyfuel Combustion

5.3.1 Technical barriers

Within this section the technical barriers of applying oxyfuel technology to the cement production process have been analysed in terms of technology integration, electrical and thermal energy demand, R&D need and potential technology providers. As described in section 4.3.2 both integration concepts - full and partial oxyfuel technology - are rated as promising and therefore taken as reference base for the technical and economic evaluation.

5.3.1.1 Integration of the technology in the cement plant

Both concepts, as described in section 4.3, are feasible to be integrated into the process with constraints to a greater or lesser degree. As a consequence of process operation and changed properties of the burning atmosphere (heat transfer, interaction with material) the process itself, the operation of the process as well as the material conversion are influenced. In the following table the concepts are compared on the basis of these factors. From this assessment, advanced safety and risk management and potential limitations can be derived.

Influence on the process:

Table 5-19 Influence on the process by the oxyfuel operation

Task	**Full Oxyfuel**	**Partial Oxyfuel**
Combustion conditions	Flame and burner characteristics have to be adapted. However, oxygen enhances the burnout of alternative fuels in the main burner (no unburnt particles can fall in the clinker bed).	No impact on main burner. Injection of oxygen and combustion gas in the calciner have to be adapted to differing volume flows and compositions
False air ingress/ Sealing	Due to the dilution of the flue gas stream, the reduction of false air ingress at the conventional locations (kiln inlet, outlet, inspection doors etc.) gain in importance.	In addition to the conventional air ingress at poke holes and inspection doors, dilution of flue gas should be reduced at connection points for material supply between conventional and oxyfuel operated string, which is a new task in cement plants.
Recirculation rate	The retrofitting requirement limits the recirculation rate to R = 0.56 – 0.52 due to the preheater function. Lower recirculation rates can be operated in new installations.	Recirculation rate is optimized at R = 0.35 - 0.4, but ability of dispersing the material in precalciner and preheater must be ensured.
Flue gas composition	CO_2 content of 80 – 85 vol.% at BAT standard operation (false air ingress, fuel input)	CO_2 content of ca. 80 vol.% at BAT standard operation (false air ingress, fuel input)
Capture rate	Capture rate is mainly subject to the CPU efficiency. 88 to 99% is possible.	Capture rate influences the process efficiency due to material fractioning in both the conventional and oxyfuel string. 60 to 70% capture is possible.
Complexity of structure	The conventional kiln plant design remains unchanged. But the recirculation of flue gas makes the overall structure more complex.	Insulation of precalciner requires a comprehensive waste heat recovery system. In combination with the recirculation of flue gas the complexity of the structure is significantly increased compared the to full oxyfuel case.

Task	Full Oxyfuel	Partial Oxyfuel
Raw material drying	In a conventional plant the flue gas is used for raw material drying, which is not possible in full oxyfuel operation to avoid dilution of the CO_2 rich stream. Only cooler exhaust air from second cooler stage can be used, which is not sufficient. The energy for higher material moisture can be provided by additional heat exchanger or additional firing.	Due to the insulation of the precalciner a lot of waste heat from the cooler, which is conventionally used as tertiary air, is available for raw material drying. Drying of high moisture contents in raw materials is possible without constraints.
Maintenance	The requirement for improved sealing adds additional effort for maintenance. One heat exchanger is operated will need to be dedusted	Sealings at connecting locations require a high level of maintenance. At least two heat exchangers are operated and will need to be dedusted

Influence on the material conversion and product quality:

Table 5-20 Influence on material conversion and product quality by oxyfuel operation

Statement	Full Oxyfuel	Partial Oxyfuel
Calcination	Depending on the material, the calcination reaction is shifted to higher temperatures by up to 80°C due to the increase of CO_2 partial pressure from 0.2 to 0.8 -0.9 bar. The recarbonation of material, which is circulated as dust in the preheater to sections of lower temperatures, becomes more important due to the higher CO_2 concentration. [ECR-09]	
Clinker formation	The formation of clinker phases is not influenced by the CO_2 content, but by the changed heat transfer in the burning atmosphere. Recarbonation of CaO by CO_2 rich cooling gases was not detected in a study, but a faster cooling rate due to the changed heat capacity of the cooling gas. [ECR-12]	No influences expected
Cement properties	No influence [ECR-12]	No influences expected

Suitability to be retrofitted:

Table 5-21 Retrofitting issues

Statement	**Full Oxyfuel**	**Partial Oxyfuel**
CPU/ASU	This state of the art technology requires space close to the plant.	
Redesign	Two-stage cooler, burner (at lower recirculation rates) and preheater changes	Precalciner, and in certain cases preheater (at least separate fans)
Refractory	Refractory lining in kiln needs to be adapted	Suitability of common refractory materials in the calciner under the changed conditions has to be proven
Impact on energy demand	The limited recirculation rate reduces the options for process optimization.	Parameter variation of optimization purposes is limited in cases where the preheater remains unchanged
Impact on capture rate	Not influenced by the retrofitting of existing plants. Only at higher raw material moisture an additional firing with unabated CO_2 emissions can reduce the capture rate by ca. 1%.	If the preheater cyclones are not modified, the requirement of material dispersion determines the process operation and less material and from this less CO_2 is introduced in the oxyfuel string. The capture rate is decreased
Recirculation loop	Space for piping and additional equipment (ORC, condenser) have to be implemented in plant structure.	Interlocking of the complex structure becomes complicated at older and tighter cement plant structures (building density)

Influence on the standard practice of operation:

In conventional kiln operation many factors require the supervisors' attention such as heterogeneity of fuels, process fluctuations, burner flame formation and observation of emission limitations. Using recirculation the requirement to manage the process parameters increases, which makes the operation even more difficult. Morover, additional plant units have to be controlled, although some gas suppliers offer so-called "over-the-fence" solutions. In addition the plant and process parameters interact with each other, therefore the risk of losing control of the process becomes higher and as a consequence more safety and controlling devices have to be installed and addiitonal special instructions for personnel is essential.

Furthermore the common way of trouble-shooting, like opening of poke-holes and inspection doors, is limited due to false air ingress. Up to a certain extent the CPU is capable to handle changes in flue gas composition caused by short-term inspections. Nevertheless the efficiency is limited by these measures. For that purpose process parameters have to be monitored better, which makes the integration of more and advanced control systems into the plant system necessary [ECR-12].

Safety issues:

In comparison to the conventional cement plant operation an oxyfuel cement plant exhibits certain risks concerning:

- Handling pure oxygen: Oxygen reduces the flammability limit of materials. Thus oxygen concentrations higher than 40 vol.% should be avoided in contact with flammable materials. Accumulation of oxygen in hot areas could cause higher explosion risk.
- Handling pure CO_2: Leakages of highly concentrated CO_2 streams could harm the environment and pose a human safety risk. The positive pressure in the plant could result in leakages. Therefore protective facilities and equipment for the employees have to be introduced even though CO_2 is not harmful in small concentrations.
- Corrosion: Higher oxygen and CO_2 concentrations influence the corrosion mechanisms. In particular the recirculation pipes will be vulnerable to these corrosion where least part of the recirculation contains gases with higher humidity. As such these tubes have to consist of stainless steel. Wet recirculation with the potential for example sulphur accumulation, could results in an even higher level of corrosion.
- Emergency shut-downs: Although a major fraction of the flue gas is not released to the surrounding, a stack is still required. Start-up, shut-downs as well as emergency shut-downs of e.g. the CPU or the pipeline require a safe release of the gases.

5.3.1.2 Energy demand

Focussing at the kiln plant the thermal energy efficiency is a reliable assessment factor. The operation of the plant and the set-up of parameters are significantly changed due to the changed burning atmosphere. As new parameters, the recirculation rate and the oxygen concentration affect the conventional dimensioning of the kiln plant.

In the case of the full oxyfuel concept the thermal energy demand depends on the recirculation rate. By decreasing this rate the oxygen concentration is increased, which benefits the process. Meeting the requirement of retrofitting an existing cement plant, the recirculation rate is limited to above 0.52 in order to assure the dispersion of material in the preheater. At too low recirculation rates the gas velocities in the existing cyclone stages are not high enough to perform this task. On a new oxyfuel cement plant the recirculation rate can be further decreased as the cyclone stages can be geometrically redesigned. Thus, at a new oxyfuel plant a higher potential of optimization exists. **Figure 5-10** shows the dependency of the fuel energy demand on the recirculation rate. The thermal energy demand is decreased down to a recirculation rate of 0.44. Until that point the advantage of less flue gas volume and less resulting waste heat is beneficial. Below this point the energy demand increases again as the volume flow is not high enough for an adequate preheating of the material to calcination temperature. Additional fuel has to compensate the disturbed capacity stream ratio of gas and material in the preheater tower. Nevertheless with a variation of the recirculation rate the fuel energy demand can be decreased up to ca. 5 % or at least kept constant.

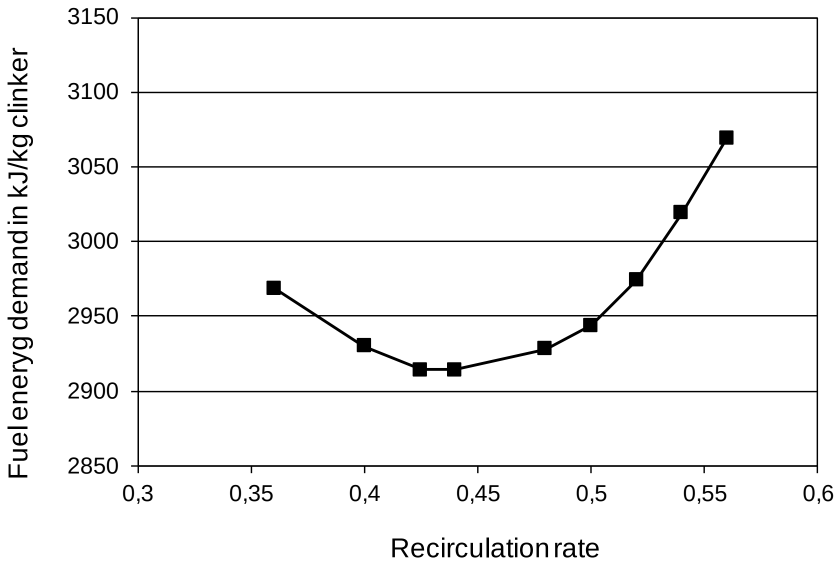

Figure 5-10 Fuel energy demand of the full oxyfuel cement plant related to the recirculation rate [KOR-13]

In the case of partial oxyfuel the conventional energy balance is different. The precalciner, which is usually supplied with gas of 900 to 1,000°C as secondary or tertiary air, is now fed with recirculated with flue gas at temperature of about 380°C when it leaves the preheater tower. To achieve a comparable temperature level of the calciner input gas as on the conventional case, an external heat exchanger has to be added. At other locations of the plant an excess of heat is available, e.g. as former tertiary air. As these gas streams are not allowed to be mixed to avoid the dilution of the flue gas, a gas-to-gas heat exchanger is used to preheat the flue gas by tertiary air. As a consequence comparable thermal plant efficiencies are not achievable due to the added heat exchanger efficiency maximum of 75%. In summary the thermal energy demand of the partial oxyfuel concept is increased by 8 -9% compared to conventional operation.

In conventional kiln operation the electrical energy demand is around 110 kWh/t cement, which is accounted by 40% on cement grinding, 20% on raw material grinding, 25% on kiln related gears and 15% on quarry related consumption (crusher etc.). The electrical energy demand of the oxyfuel technology is mainly due to the energy intensive air separation unit (ASU) and flue gas conditioning CO_2 processing unit (CPU). In contrast to the full oxyfuel design only oxygen for the operation of the precalciner is needed in the partial oxyfuel design and a smaller gas volume of flue gas has to be treated by the CPU. The recirculation and the separation of gas streams also need additional power especially for fans, condenser etc. Thus the power demand is substantially increased by 86% per tonne of cement in the partial oxyfuel case and 118% in the full oxyfuel case. Accordingly in the partial oxyfuel case more than half of the power is still required for the base demand of fans, conveyors, mill and kiln gears but in the full oxyfuel case the additional equipment for CO_2 capture requires more electrical power than is needed in the reference scenario for conventional kiln operation. (compare **Figure 5-11**).

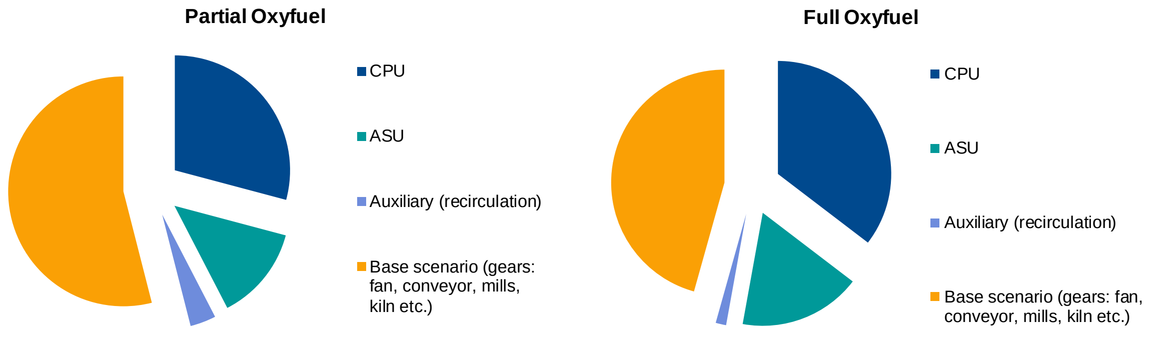

Figure 5-11 Electrical energy demand of the oxyfuel process

As a rule of thumb a doubling of the electrical energy demand can be assumed when applying the oxyfuel technology.

5.3.1.3 R & D status and needs

Based on the above consideration some issues are still not solved:

- Calciner operation: When applying the partial oxyfuel concept the calciner operation is significantly impacted. In principle the lower the recirculation rate is, the lower is the thermal energy demand. Therefore, the calciner is operated at lower volume flows and under different gas properties. To calcine the material and to make the fuel ignite certain conditions have to be fulfilled. The exact design of this calciner and how to inject the oxygen still needs some development.
- Impact of the oxyfuel operation on material cycle formation and bypass system: Due to economic and environmental reasons the application of alternative fuels is an important issue for the cement industry. At higher fuel substitution rates and depending on the fuel composition, cycle generating elements like alkalis, sulphur and chlorine might be introduced to the kiln. At higher levels this can form internal cycles (by evaporation and condensation), which cause coatings and therefore plant disturbances. Concerning the partial oxyfuel concept it is unknown, how these cycle generating elements are enriched in the recirculation, as a condensation stage is not included in order not to further decrease the thermal energy input. In order to relieve the system a bypass system of kiln gases (or material) might become necessary at higher alternative fuel rates. To avoid emissions with the gas bypass stream, it has to be treated separately. Cold flue gas or oxygen has to be mixed to the bypass stream for quenching and subsequently added to the recirculation stream. In case of full oxyfuel this cooled recirculated flue gas enhances the heat exchange in the clinker cooler. When using the partial oxyfuel concept, this is counterproductive as the flue gas temperature has to be increased.
- Behaviour at switching mode: For start-ups and shut-downs a switching mode between conventional and oxyfuel operation has to be established. To balance the streams and determine an optimal method still needs consideration. The more the plant structure and the process parameters are adapted to the oxyfuel operation, the more complex the switching mode will need to be. Using a bespoke waste recovery system to operate the

process in the case of partial oxyfuel, the start-up becomes more complex due to the interdependencies of the heat flows.

- Power demand: Reduce electricity demand by applying low energy oxygen supply or CO_2 purification
- CO_2 purification: Although the technology of CO_2 processing units is known, large scale units are still to be proven.

Although the full oxyfuel concept influences the whole kiln plant operation, more uncertainties and resulting R&D needs are identified. Nevertheless as described in section 4.3.1 several basic research studies have been conducted in the past few years. At this point of development a reasonable next step would be the testing in pilot scale. A pilot plant would require extensive engineering work in terms of design, dimensioning, structure and scaling effects. In a final step the operation of a pilot plant could verify the theoretical findings from previous studies, like:

- start-ups / shut downs or in general switching mode from conventional to oxyfuel operation
- operational mode and adjustment of the process parameters
- burner design and operation
- clinker and cement quality
- long-term tests on refractories
- flue gas composition at different operational modes
- sealing aspect (improved maintenance) in long-term operation
- energy and mass balances based on experimental data
- impact of the changed burning atmosphere on volatiles (implying coatings and internal cycles of sulphur, chlorine and alkalis in the kiln plant)
- in a later stage: switch to alternative fuels
- identification of plant-specific impacts (influenced by the size or surrounding aspects) and general statements

Currently only one announced project by ECRA is aiming at the development an oxyfuel pilot cement plant. Even if all the engineering equipment is available, the construction of such a plant would require support by funding. Assuming that the technical development is further supported, a first large-scale application could be technically feasible by 2025 at the earliest. Only after this date can a full scale application in the cement sector could be envisaged. However, from an economic point of view, the time frame will to a large degree depend on substantial funding, availability of storage sites, legal framework as well as on public acceptance.

5.3.1.4 Technology providers

In general the technology or the knowledge for development needed for an oxyfuel cement plant is available. Air separation units are state-of-the-art technology and can be supplied by gas producers. Theoretical studies on large-scale CO_2 processing units for cement plant applications have been executed [ECR-09], but such plants still need to be proven. Plant engineers of different disciplines are able to construct the modified plant components such as the two-stage cooler or burner design. Potential technology providers for the modifications at an oxyfuel cement plant are therefore typical cement plant manufacturers but with the support from technology providers with experience in handling gases.

5.3.2 Cost estimation

On the basis of the reference scenario the cost estimation of the oxyfuel scenario has been determined. Both methods, the partial and the full oxyfuel concept, have been evaluated concerning the increase of production costs. Moreover costs for retrofitting and for new installations have been differentiated. The production costs are estimated based on the sum of:

- Capital costs on the basis of total investment (**Table 5-23**)
- Variable operating costs (**Table 5-24**)
- Fixed operating costs (**Table 5-25**)

The equipment costs for the units CPU, ASU, ORC and the auxiliary devices of the recirculation – as described in section 4.3 - represent the added investment costs to that of a new build cement plant (**Table 5-22**). The retrofitting of existing plants requires the modification of certain plant equipment such as the cooler or calciner, which implies related equipment costs. An additional 5% of this equipment costs is added to match the reconstruction of existing equipment (control system etc.) Deconstruction of obsolete plant units and costs for down-times are excluded.

Table 5-22 Oxyfuel scenario: Equipment costs

Equipment	**Full Oxyfuel based on [ECR-09]**	**Partial Oxyfuel [IEA-08]**
Organic Rankine Cycle	9.0 M €	8.3 M €
Air separation unit	10.9 M €	9.0 M €
CO_2 processing unit	9.5 M €	7.6 M €
Recirculation (incl. fan, piping, filter, heat exchanger, condenser)	3.6 M €	1.8 M €
Calciner/Preheater modification*	-	1.5 M €
Cooler modification/sealings*	3.0 M €	-

* In case of retrofitting an existing plant

In addition to the equipment costs, the installed costs include the civil, engineering, designing and steel work as well as the erection. After adding 10% of the installed costs for the contingency and fees the total plant cost may be estimated. In summary, the implementation of partial oxyfuel requires less investment due to the smaller construction of ASU/CPU and ORC because of the lower gas volumes.

Table 5-23 Oxyfuel scenario: Investment costs

Item	**Full Oxyfuel based on [ECR-09]**		**Partial Oxyfuel based on [IEA-08]**	
	Retrofit	New installation	Retrofit	New installation
Equipment costs	37.8 M €	110 M €	31.0 M €	104 M €
Installed costs	78.8 M €	229.2 M €	64.5 M €	216.7 M €
Total plant costs	86.7 M €	252.1 M €	71.0 M €	238.4 M €
Total capital required	103.7 M €	290.7 M €	85.1 M €	275.1 M €

The increase of variable operating costs compared to the base scenario is predicted based on the additional power supply for the capture of CO_2. In line with the estimated energy demand in section 5.3.1.2 the expenditure for electrical energy is doubled on average, while the expenditure for fuels is nearly constant. In the case of full oxyfuel for retrofitting existing plants the thermal energy input remains equal, while the fuel demand in partial oxyfuel operation is slightly increased. Both concepts deliver lower fuel costs for new installations due to the higher assumed energy efficiency and a higher value for the retrofitting of an existing plant. The partial oxyfuel design delivers less variable operating costs by the reason of lower power demand.

Table 5-24 Oxyfuel scenario: Variable operating costs

Item	**Full Oxyfuel**	**Partial Oxyfuel**
Raw materials	3.7 €/t cement	3.7 €/t cement
Fuel, kiln plant	5.3 – 6.2 €/t cement	6.2 – 7.3 €/t cement
Power, capture	9.2 €/t cement	7.2 €/t cement
Power, kiln plant	8.8 €/t cement	8.8 €/t cement
Cooling water	0.24 €/t cement	0.23 €/t cement
Process water	0.02 €/t cement	0.02 €/t cement
Misc.	1.1 €/t cement	1.1 €/t cement
Total	29.0 - 29.3 €/t cement	27.3 - 28.4 €/t cement

As the complexity of the process rises, in both cases the costs for maintenance and operational staff are assumed to be increased by 25% compared to the base case. Insurance and local taxes rely on the installed costs (1%) and therefore differ slightly between full and partial oxyfuel design.

The production costs are composed of the capital charges, the variable and fixed operating costs. The calculation of the capital charges has been made on the basis of equivalent annual costs. In the case of retrofitting it was assumed that the existing cement plant is already paid off. In summary the production costs increase by 42% in full and by 36% in partial oxyfuel operation.

Table 5-25 Oxyfuel scenario: Fixed operating costs

Item	**Full Oxyfuel**	**Partial Oxyfuel**
Maintenance	6.3 €/t cement	6.3 €/t cement
Operational labour	6.9 €/t cement	6.9 €/t cement
Administration	2.8 €/t cement	2.8 €/t cement
Insurance costs	1.1 €/t cement	1.0 €/t cement
Local taxes	1.1 €/t cement	1.0 €/t cement
Total	18.2 €/t cement	18.0 €/t cement

Table 5-26 Oxyfuel scenario: Production costs and CO_2 avoidance costs

Item	**Full Oxyfuel**		**Partial Oxyfuel**	
	Retrofit*	New installation	Retrofit*	New installation
Investment costs	103.7 M €	290.7 M €	85.1 M €	275.1 M €
Capital charges	9.0 €/t cem*	25.2 €/t cem	7.4 €/t cem*	23.8 €/t cem
Fixed operating costs	18.2 €/t cem		18.0 €/t cem	
Variable operating costs	29.3 €/t cem	29.0 €/t cem	28.4 €/t cem	27.3 €/t cem
Production costs***	56.5 €/t cem*	72.4 €/t cem	53.8 €/t cem*	69.1 €/t cem
Increase of production costs		42%		36%
CO_2 avoidance costs (direct emissions)**	41.2 €/t CO_2	39.1 €/t CO_2	53.8 €/t CO_2	49.2 €/t CO_2
CO_2 avoidance costs (indirect emissions)****	45.2 €/t CO_2	43.0 €/t CO_2	60.3 €/t CO_2	55.2 €/t CO_2

*Assumption: Existing cement plant is already paid off

** Excl. transport and storage, indirect CO_2 emissions

*** Excl. freight, raw material deposit, land property, permits etc.

**** Excl. transport and storage, including power emissions from grid

For the determination of the CO_2 avoidance costs (excluding transport and storage) a capture rate of 90% at full oxyfuel concept (0.55 t CO_2/t cement) and of 65% (0.37 t CO_2/t cement) at partial oxyfuel has been reported. Including the indirect emissions from power production the abated CO_2 emissions are reduced to 0.50 t CO_2/t cement in case of full oxyfuel technology and 0.33 t CO_2/t cement in case of partial oxyfuel technology.

Although the increase of production expenditure is higher using the full oxyfuel concept, the resulting CO_2 avoidance costs are lower as a consequence of the higher capture rate. The avoidance costs of retrofitting the cement plant (assuming that the existing plant is paid off in the baseline scenario) are as high as for the new installation.

A sensitivity analysis for the CO_2 avoidance costs has been calculated for the non-European regions (**Figure 5-12** and **Figure 5-13**), economic plant life (**Table 5-27**) and variation of energy and material prices (**Figure 5-14** and **Figure 5-15**) using the assumptions made in section 5.1.

The sensitivity to regions outside the European Union, specifically for the regions Middle East and China, results for both oxyfuel concepts in a decrease of production costs up to ca. 45 - 50%. In the Chinese region the capital costs are more decisive, while the variable costs are higher compared to the Middle Eastern region.

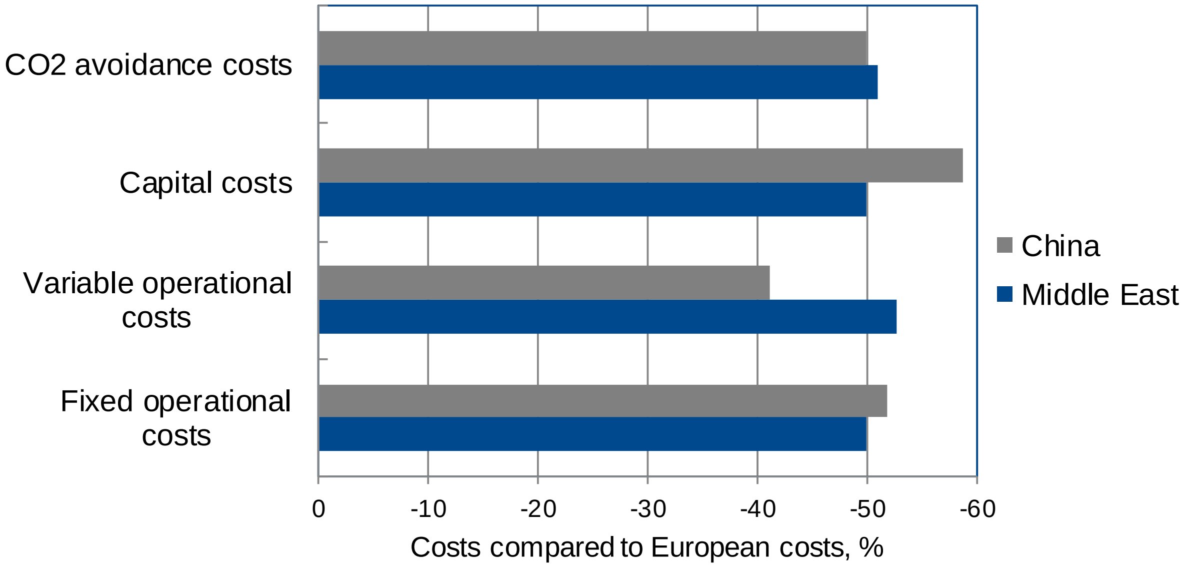

Figure 5-12 Sensitivity to Non-European regions, full oxyfuel

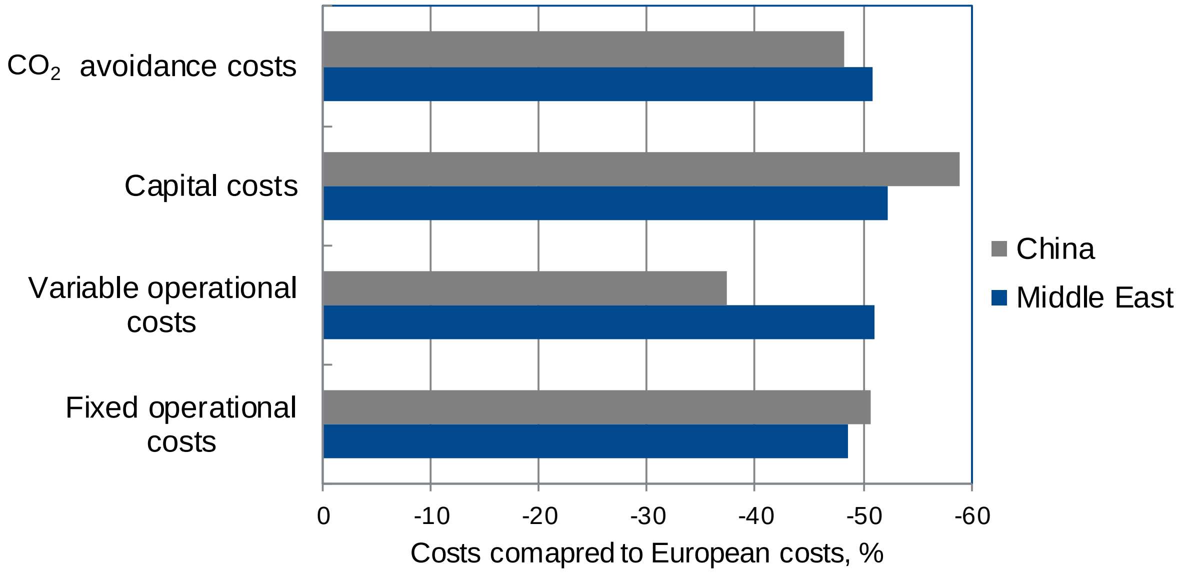

Figure 5-13 Sensitivity to Non-European market, partial oxyfuel

Cement plants are usually planned to operate for more than 40 years. Assuming this life time as payback period, the production costs by means of annual capital charges are decreased by 3.5% (**Table 5-27**). This results in lower CO_2 avoidance costs, with similar effects for both concepts.

Table 5-27 Oxyfuel scenario: Sensitivity to economic plant life of 40 years (related to new installation)

Item	**Full Oxyfuel**	**Partial Oxyfuel**
Capital charges (40 y)	22.5 €/t cement	21.3 €/t cement
Production costs (40 y)	69.7 €/t cement	66.6 €/t cement
Decrease of production costs compared to 25 y plant life	3.7%	3.6%
CO_2 avoidance costs (direct emissions)* (40 y)	34.2 €/t CO_2	42.4 €/t CO_2
CO_2 avoidance costs (indirect emissions)** (40 y)	37.6 €/t CO_2	47.6 €/t CO_2

* Excluding transport and storage, indirect CO_2 emissions

** Excluding transport and storage, including power emissions from grid

In the final step the sensitivity of operating costs to price variations has been investigated. **Figure 5-14** and **Figure 5-15** illustrate the development of operating costs with varying the energy and material prices in a range between -25% and + 25%.

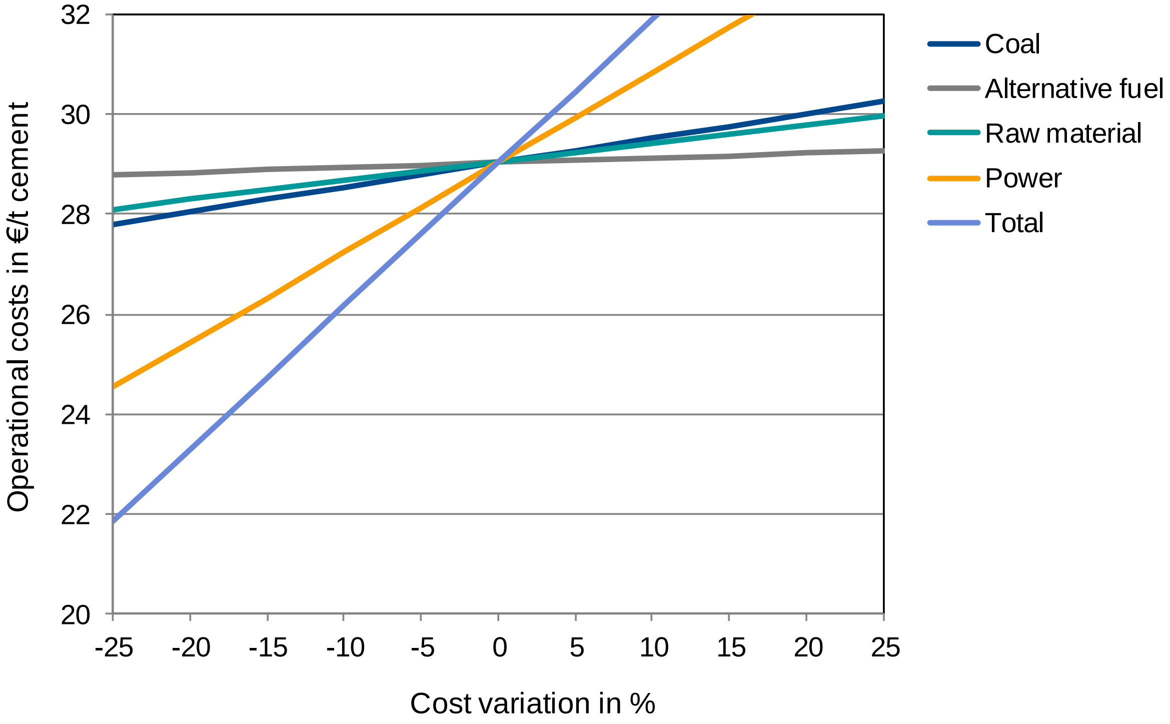

Figure 5-14 Sensitivity to operating costs, full oxyfuel

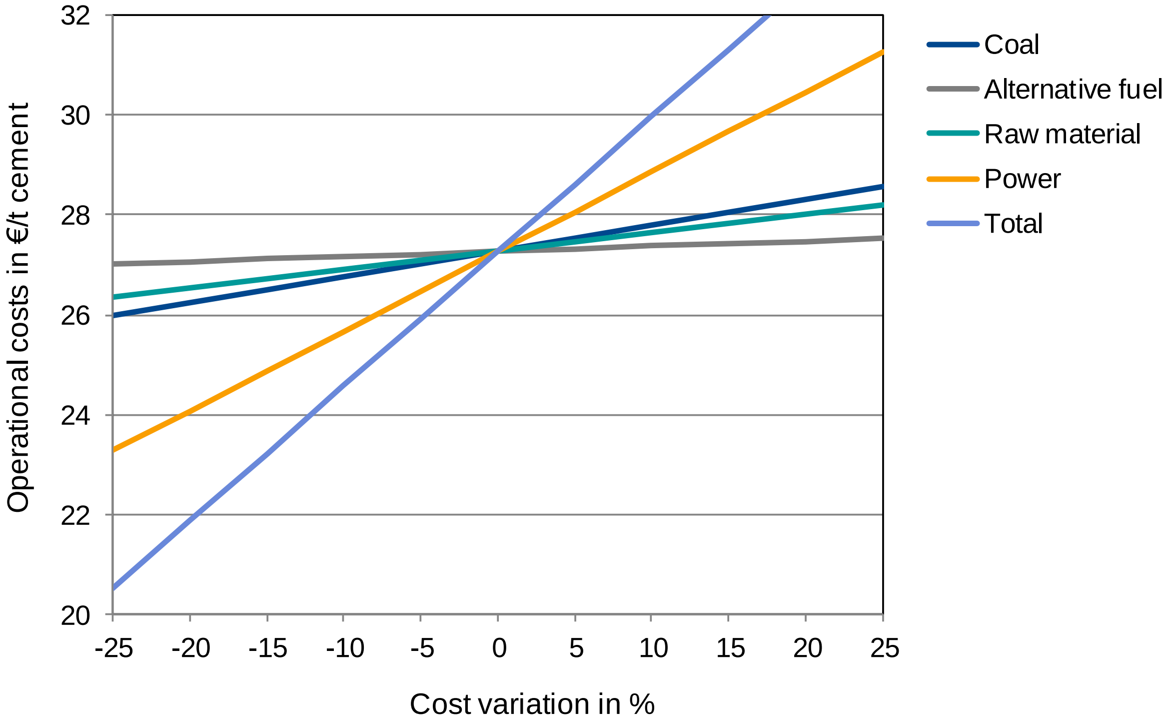

Figure 5-15 Sensitivity to operating costs, partial oxyfuel

The sensitivity of fuel and raw material prices especially on full oxyfuel operating costs is comparably low. Due to the high demand of electrical power, the sensitivity of the operating costs is quite high. For maximum +25% and minimum -25% of the operating costs, the production costs are varying by 10% in full and by 9.7% in partial oxyfuel operation (**Table 5-28**). Due to the lower dependency on the power supply which is the main cost driver, the total operating costs of the partial oxyfuel concept are less sensitive to variations although fuel prices are an influencing factor.

Table 5-28 Oxyfuel scenario: Sensitivity to variable operating costs (related to new installation)

Item	**Full Oxyfuel**		**Partial Oxyfuel**	
	- 25%	+ 25%	- 25 %	+ 25%
Operating costs	21.8 €/t cem	36.2 €/t cem	20.5 €/t cem	34.0 €/t cem
Production costs	65.2 €/t cem	79.6 €/t cem	62.3 €/t cem	75.8 €/t cem
Difference of production costs	- 10.0%	+ 10.0%	- 9.7%	+ 9.7%
CO_2 avoidance costs (direct emissions)*	26.1 €/t CO_2	52.3 €/t CO_2	30.8 €/t CO_2	67.3 €/t CO_2
CO_2 avoidance costs (indirect emissions)**	28.6 €/t CO_2	57.4 €/t CO_2	34.6 €/t CO_2	75.5 €/t CO_2

* Excluding transport and storage, indirect CO_2 emissions

** Excluding transport and storage, including power emissions from grid

5.4 Conclusion

Based on section 5 of this report the technical/economic barriers and potentials concerning the application of both oxyfuel technology (full and partial) and of chemical absorption as part of the post-combustion capture were evaluated.

Technical barriers to the use of chemical absorption for CO_2 separation are mainly the flue gas composition in terms of SO_2 and NO_x components and trace impurities, which harm the solvent in higher concentrations and might require secondary abatement techniques. Space and health and safety requirements can also constitute a constraint and the treatment or disposal of waste solvents requires additional consideration. The reboiler of the solvent as an energy intensive addition to the system requires around 150 MW_{th} energy of the reference 1 Mt/y plant based on a widely used solvent (MEA). Alternative solvents with substantially lower energy consumption are being developed and in some cases used commercially. As the cement plant only provides waste heat for 15% of the solvent regeneration energy demand, an additional combined heat and power (CHP) plant is needed, from which the CO_2 emissions can be simultaneously be captured. For the additional energy demand two options are considered, a coal fired plant or a natural gas combined cycle (NGCC) plant. The optimum choice will depend on local conditions and fuel prices. Synergies between these two facilities – cement and power plant – can be achieved by the operation of a calcium looping process for CO_2 capture. The problem of waste sorbent disposal can be solved as deactivated sorbent from this CO_2 capture process could be reused as raw material in the cement clinker production.

The oxyfuel technology can be integrated in the clinker burning process using two different concepts – full or partial integration. Both concepts seem likely to be suitable for retrofitting existing plants, although the plant specific space availability in the structure may limit the construction and therefore the deployment. As integrated systems, both concepts influence the process and the material conversion and therefore require certain levels of operational adaptations. Therefore, the effort for operating and controlling such a plant rises. When handling pure gases like oxygen and carbon dioxide advanced health and safety measures are required. While the thermal energy demand is only affected to a small extent, the electrical energy demand is doubled per tonne of produced cement. R&D is still required for some conceptual considerations e.g. concerning the implementation of a kiln bypass system. For further investigations, in particular on different operational modes, a pilot-scale facility would be necessary.

The development of CCS in the cement industry has been initiated in recent years through different research studies and laboratory tests. For the Post-combustion technology – as an end of the pipe approach – the cement industry can take advantage of existing experience mainly in the power sectors. Oxyfuel technology, however, requires a more dedicated approach because it has to be adapted to cement kilns and requires a much more advanced degree of research and development when compared to Post-combustion. The timeframe for the development of CCS in the cement industry is therefore different for the two approaches.

From a pure technical point of view, a full scale Post-combustion installation in the cement industry will not be able to operate earlier than 2020 due to the necessary adaptation of the proven system to cement kilns and its testing in large-scale. An Oxyfuel cement installation will require more time to gain experience in pilot and demonstration plants and is therefore not expected to operate as a full plant before 2025. Only after these dates is widespread deployment expected to be possible in the cement industry.

Figure 5-16 illustrates the economic comparison in terms of CO_2 avoidance costs of the two capture methods. Capture costs are subject to different future developments (e.g. development of the technology and learning curve, development of emissions limits concerning NO_x, SO_2 etc.) so estimation is challenging. Therefore, a range is given which is based on the above sensitivity analysis. The darker blue range represents the expected avoidance costs taking the today's trend of policy and prices into account. The lighter blue range shows the costs if prices of energy and consumables decrease by -25% which seems unlikely from today's perspective (according to **Table 5-28** and **Table 5-18**).

In essence the full oxyfuel technology shows lower capture costs, whereas the costs of the full and partial integration concepts overlap. With regard to the post-combustion capture the combination with an NGCC process seems to be least costly and under certain circumstances as costly as oxyfuel capture.

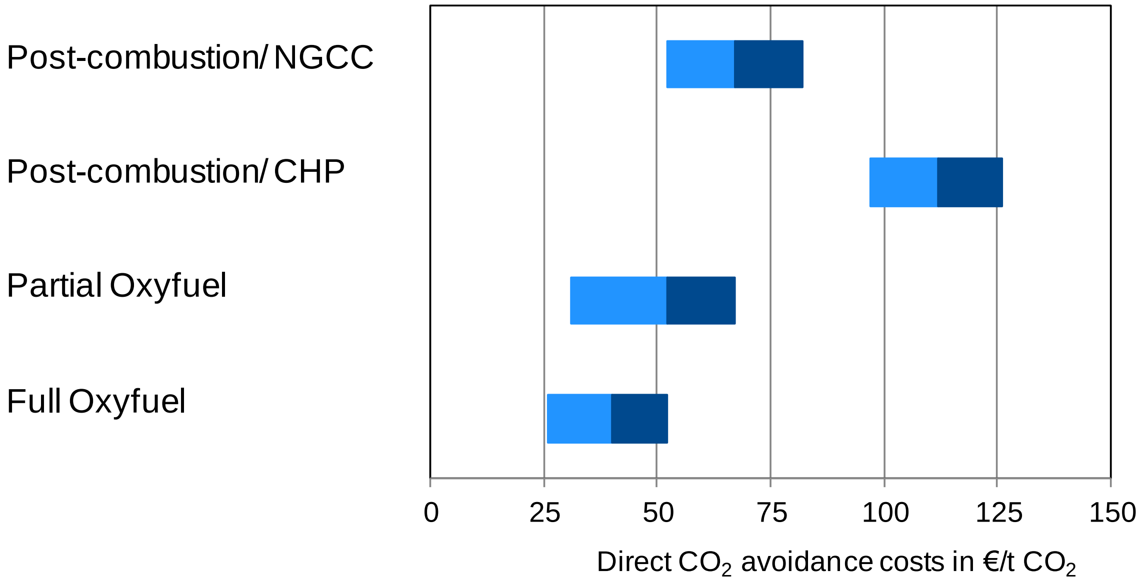

Figure 5-16 Comparison of direct CO_2 avoidance cost (excl. transport and storage and indirect CO_2 emissions) for different capture technologies for the reference cement plant

In summary the economic assessment showed that the production costs will be increased by 36 to 110% when applying carbon capture technologies. In the case of the oxyfuel technologies this cost increase is mainly driven by the additional electrical energy demand. The main cost drivers of the post-combustion capture are both additional power and fuel energy demand in addition to the (at least) doubled investment costs. Post-combustion technology studies show that a symbiosis of a cement plant with a power plant which results in a joint CO_2 capture plant (calcium looping) could further reduce the specific CO_2 capture costs significantly [ROM-11]. Thus under certain conditions both methods post-combustion and oxyfuel can be comparable with regard to economics. Assuming that the cement industry would be charged for indirect emissions of consumed energy or supply of energy to the grid the indirect CO_2 avoidance costs for both technologies are broadly comparable (Oxyfuel 40 - 60 €/t CO_2 and post-combustion 50 - 100 €/t CO_2).

Nevertheless there are still economic barriers which inhibit an enhanced development of carbon capture technologies in the cement sector. Currently, the legal and economic conditions of these technologies would impair the competiveness of cement production.

6 Governmental policies and initiatives to support CCS deployment and other CO_2 reduction techniques in the cement industry

The following chapter describes policies and regulations concerning available CO_2 reduction methods and the implementation of CCS technologies with the main focus on Europe as the defined reference location. To widen the scope to worldwide policies examples of Chinese, Indian, US or other regulations are also given.

6.1 Current CO_2 related policies and regulations

Greenhouse gas emissions reduction is currently subject to different national and international climate programs. Various approaches are summarized as follows:

- European Union

  The EU - Emission Trading System (ETS) is now in its third phase following the pilot phase from 2005 to 2007 and phase II from 2008 to 2012. The price for the allowances is determined by the market which reacts to supply and demand based on an overall cap. Currently the CO_2 price of 3 – 5 € in the European scheme reflects the lower CO_2 emissions due to the financial and economic crisis in Europe since 2008. In 2013 the EU Commission therefore initiated to discuss “structural measures” for a reform of the EU-ETS aiming for a higher CO_2 price to fulfill the expectations of politics.

  To what degree industry can pass on CO_2 costs depends on many factors. Since the ETS is not a “closed system” it carries the risk of carbon leakage, i.e. the relocation of CO_2 emissions to countries without such CO_2 costs. This would not only undermine the aims of the system but would also lead to the relocation of investments and ultimately whole industries. To minimise carbon leakage the EU-ETS uses the free allocation of allowances for industries subject to carbon leakage. In this case allocation is based on a benchmark defined by the 10% of installations with the lowest specific CO_2 emissions multiplied with the installation’s base year activity (historic production). This underlines that even under free allocation operators are not fully protected if their production rises above their base year activity or if their specific CO_2 emissions are higher than the benchmark. The cement industry is listed as a sector vulnerable to carbon leakage [MCK-08]. By the end of 2014 the EU Commission will revise the list of “sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage”. Sectors or subsectors on this list will be allocated allowances for free based on a benchmark. For all other sectors the corresponding free allocation is decreased to 80% in 2013 further to 30% in 2013 of the initial amount.

- USA

  The US has no climate policy on a federal level. On the other hand several state regulatory initiatives have been implemented. California enacted the comprehensive Global Warming Solutions Act in 2006 to reduce GHG emissions through a combination of regulatory and market mechanisms. Under this Act, California established a cap and trade program for major sources with enforceable compliance obligations beginning with 2013 emissions. California is also partnering with British Columbia, Ontario, Quebec and Manitoba in the Western Climate Initiative to develop a cap and trade program that transcends national boundaries. The Regional Greenhouse Gas Initiative – a cooperative effort among nine Northeastern and Mid-Atlantic states to reduce GHGs through a market-based cap and trade program – completed its first three year control period in 2011.” [GCI-13]

Moreover the United States Environmental Protection Agency (EPA) is taking a common-sense approach to develop standards for greenhouse gas emissions from mobile and stationary sources which also include cement plants under the Clean Air Act. Within this approach greenhouse gas emission data from large emission sources across a range of industry sectors are collected by the Greenhouse Gas Reporting Program.

- Australia

  Australia’s Gillard government put a carbon tax on direct emissions from facilities which emit more than 25,000 t/yr CO_2 although not applied to agriculture and transport in 2012. Thus the majority of the Australian carbon tax is paid by a limited number of companies. The government elected in 2013 is seeking to repeal this tax system and to develop an action plan to enhance emission reduction.

- Others worldwide

  Although several countries (like Japan, Canada, Norway, Sweden, Netherlands etc.) introduced different national carbon tax systems, a global agreement on CO_2 emission reductions e.g. in the framework of the UNFCCC with one common target and price for CO_2 does not exist. Some nations which do not apply any tax or trading systems are also discussing to include CO_2 in their emission reduction regulations and therefore enforce the reduction within industry.

6.2 Current policies and regulations concerning CCS

Carbon capture is discussed as a technology to reduce CO_2 emissions beyond the reduction potential of conventional mitigation methods. It is regarded as indispensable measure by some stakeholders such as IEA in order to reach the 2050 80% CO_2 emission reduction aim on a global level. For this reason CCS is seen as a key technology for GHG reduction in many national and international programs (e.g. in China’s National Climate Change Program). The deployment of carbon capture technologies requires the regulation of the infrastructure for all relevant steps of the CCS chain, including a legal framework for CO_2 transport and storage, monitoring and verification and licensing procedures. Some countries are establishing or developing such legal frameworks.

- European Union

  Since 2009, EU legislation on geological storage of CO_2 (Directive 2009/31/EC on the geological storage of carbon dioxide, “CCS directive”) has been in force. It should provide the necessary regulatory framework to ensure that CO_2 will be safely and permanently stored underground. The incentive to deploy CCS shall be given by the revised ETS Directive, which includes CCS explicitly in Annex I countries, and considers emissions captured, transported and stored as not being emitted.

  According to the EU Commission “Carbon dioxide capture and geological storage [CCS] is a bridging technology that will contribute to mitigating climate change. […] Its development should not lead to a reduction of efforts to support energy saving policies, renewable energies and other safe and sustainable low carbon technologies, both in research and financial terms" (EU CCS Directive). Furthermore the CCS Directive gives EU member states the right to ban storage in parts or in the whole of their territory. This may accommodate any risk for the environment and human health to be assessed with regional knowledge.

Today the acceptance of CO_2 storage is still very low in Europe [EUC-11]. Importantly , the main obstacle is the missing legal framework infrastructure for the transport of the captured CO_2 to a suitable storage site.

Industry however requires a cost efficient and predictable legal framework for its long term investments, including the long-term liability for $CO_{2.}$ As outlined in chapters 4.2.5 and 4.3.2 the costs for post-combustion technology and oxyfuel combustion are estimated to be higher than 40 € per tonne of CO_2. Transport and storage costs have to be added to this, resulting at CO_2 abatement cost of at least 50 up to 100 € per tonne of CO_2 for a cement plant.

- USA

  The US permitting guidance under the Prevention of Significant Deterioration (PSD) involves an analysis of the Best Available Control Technology (BACT) and identifies CCS as an add-on pollution control technology that is 'available' for facilities emitting CO_2 in large amounts. Moreover CCS could be listed as an option of the BACT process for such facilities, which does not necessarily mean CCS must be selected as BACT as case-specific factors may warrant elimination of CCS as an option at later steps [GCC-13].

  The US can rely on well-established EOR (Enhanced Oil Recovery) regulations, which include technical aspects (like safety, handling etc.). Several regulations could also be applied to CO_2 injection, but these regulations are not designed for this purpose. Therefore, the US EPA has issued rules for the regulation of underground injection of CO_2 under the Safe Drinking Water Act.

- India/China

  China is recently enforcing CCS R&D projects and is expected to develop suitable CCS regulations. The Indian government has not addressed CCS since geological capacity for CO_2 storage is limited. Instead a focus on carbon capture is on algal growth and its use as biomass [CSI-13]. China has an established EOR regulation which appears to be the preferred CO_2 storage option so far.

Finally legal certainty regarding the long term liability for the CO_2 stored is lacking worldwide. It is not clear at present whether the liability for the stored CO_2 will rest with the CO_2 transportation and storage operator or with the emitting industry e.g. the cement producer [GCI-13].

6.3 Policies with respect to other CO_2 abatement options

There are basically four options using conventional methods to save CO_2 emissions in the cement industry. These are the increase of energy efficiency (section 6.3.1) – thermal and electrical – by deployment of existing state of the art technologies in new cement plants, and retrofit of energy efficient equipment where economically viable, the application of alternative fuels and (precalcined) raw materials (section 6.3.2), and clinker substitution in the cement (section 6.3.3), taking quality requirements into account as described in section 3.1.4.

6.3.1 Increasing energy efficiency

The European Union has implemented an Energy Efficiency Directive (21012/27/EG) to establish a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Union's 2020 20% headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date. The major content of this directive are rules designed to remove barriers in the energy market and overcome market failures that impede efficiency in the supply and use of energy. It also provides for the establishment of indicative national energy efficiency targets for 2020 [EU-13]. The EU Directive has to be implemented in national legislation in all member states. Furthermore, in some countries industry has implemented voluntary agreements aiming at improving energy efficiency.

6.3.2 Use of alternative fuels and raw materials

With respect to waste policy an advantage of the use of waste as alternative fuels is unique since its energy and its material are utilized at the same time. The mineral fractions as well as the ashes contribute to the raw material for the clinker production. In addition to the various recycling options landfilling is still a very common waste management option, which restricts the production of alternative fuel for the cement industry.

- European Union

  The European Industry Emissions Directive (IED) unites and adopts previous environmental directives, among others the Directive on Integrated Pollution Prevention control (IPPC) and the Waste Incineration Directive (WID). Member states had to implement the new IED provisions by January 2013. The IED introduces uniform environmental standards in Europe by implementation of the so-called Best Available Techniques (BATs).

  The use of alternative fuels in the cement industry can also be restricted by the availability of certain waste materials. This is caused by different competing waste management options, as given in a waste hierarchy described in the EU Waste Framework Directive. According to this hierarchy material recycling has a preference over energy recovery, which in turn is higher in the hierarchy than incineration and landfilling.

- USA

  In the US the Commercial and Industrial Solid Waste Incineration (CISWI) rule defines a new category of emission limits for cement kilns using solid wastes in 2011. This requires additional abatement technologies like preprocess (raw materials), in-process (solids extraction) or afterprocess (polishing filter) methods, which might impair overall energy efficiency again.

- India/China

  In case of India, where less than 1% of the cement industry's fuel energy demand is covered by alternative fuels, the rapid urbanization during the recent decades indicates a further increase of urban population and therefore increased municipal wastes in the coming years. This forces the country to advance its municipal solid waste management, which could implement the use of wastes as alternative fuels in the cement industry

[CSI-13]. The Indian offices of the Institute for Industrial Productivity “has established a Forum of Regulators comprising high-level representation from various State Pollution Control Boards. The Forum is part of a multi-stakeholder initiative launched in India to draw up an implementable action plan to increase the substitution rate [of alternative fuels and raw materials] in the Indian cement industry from the present level of less than 1% to 15% by 2020.”[IIP-13] In the meantime the “Goa State Pollution Control Board (GSPCB) has signed a memorandum of understanding with a cement company to use the plastic waste generated across the state as fuel for its manufacturing plant.” [GCN-13]

Similar developments to introduce rules to increase the use of waste treatment to provide alternative fuel for cement kilns are expected to be developed in China [GCN-13].

In all cases a proper collection logistic and treatment of the waste is a prerequisite to provide for wastes as alternative fuels in cement plants. Although temperatures in cement kilns are high enough to destroy hazardous elements public concerns are existing towards the application of some synthetic solvents or biological wastes (sewage sludge or animal meal). However the main challenge remains that in some regions of the world the use of alternative fuels in the cement industry still lacks social acceptance thus limiting the potentials to take advantage of their contribution to CO_2 reduction.

6.3.3 Reduction of clinker/cement ratio

Clinker can be substituted in cement by other mineral components such as ground granulated slag from blast furnaces, fly ash from coal fired power stations, burnt shale or volcanic or natural pozzolanic materials. Also finely-ground limestone can be used as a main constituent in cement. As a general rule the CO_2 emissions per tonne of cement are lower for lower clinker/cement ratios. However, this is limited not only by the availability of appropriate materials but also by the requirements from concrete performance depending on the individual construction.

- European Union

  The European Cement Standard Cements EN 197-1 describes common cements according to their composition. It comprises 27 types of cement and it is foreseen that new cements will be standardized in the near future. The latter includes so called ternary cements comprised of clinker and two other main constituents. The combination of these constituents with its dedicated properties ensures good cement performance in concrete and mortar including durability aspects. Different types of ternary cements have been suggested for standardization, with clinker contents of 50 to 64 wt.% and 35 to 49 wt.% respectively. It is expected that more types of cements, with 4 constituents as quaternary cements, will be submitted for standardization. These cases will require proof of the cement performance in mortar and concrete and, whenever new main constituents may be introduced, its environmental performance.

- USA

  The US cement standard ASTM does not categorize cements in groups with different constituents but takes into account their chemical and physical requirements. Thus the ASTM includes performance based specifications for hydraulic cements with no direct restrictions on compositions.

- India

  Indian and European cement standards are similar. As compared to the European standard the Indian cements are coarser ground and exhibit different strength development. This is not only due to different reference methods for strength testing according to the respective standards but also due to different building traditions. The principle non-clinker constituent in Indian cements is fly ash. Limestone as a main constituent is not foreseen by the Indian cement standard. Like in any other country cements in India reflect the local conditions with respect to the market, the availability of the various materials and the ambient conditions. The particle size distribution being coarser than in other regions of the world corresponds with a lower demand for grinding energy per tonne of cement [Hoe-13].

6.4 Funding mechanisms to develop capture technologies

The development of capture technologies to a commercial scale will at a certain stage require pilot and demonstration projects. However, the stakeholder consultation (Chapter 3.5) has shown that due to the high costs involved, cement producers are in the position to make significant investments into demonstration projects. Furthermore, even if the investment cost was funded to a large degree, the operational costs would still be too high.

Some funding programmes are known for the development of CCS especially for the power sector or for developing industrial CCS demonstration plants. Dedicated funding for the cement industry is not available at present. Examples for current funding mechanisms are named below:

The UK CCS Commercialisation Competition and the UK Electricity Market Reform makes available £1 billion funding to support the practical experience in the design, construction and operation of commercial-scale CCS in the power sector including the development of early infrastructure for carbon dioxide transport and storage. Fundamental research on storage, development and pilot of capture in power generation is funded with £125 million in a 4-year research, development and innovation programme. Additionally the Tees Valley Unlimited (a local enterprise partnership) announced the Tees Valley City deal offering £ 34 million in December 2013. Part of this deal is focusing on taking industrial CCS forward [TVU-13].

The EU supports demonstration projects by 300 million emission unit allowances (EUAs) from the New Entrance Reserve (“NER 300”) to fund up to 12 large-scale CCS demonstration projects. The deadline for the submissions of proposals was 3 July 2013, however only one application for a demonstration project was filed up to this time. Another EU initiative uses the EU Energy Program for Recovery (EEPR) in which €1 billion has been reserved for CCS demonstration projects to finance 80 % of the costs of a carbon capture and storage project.

In Canada CCS projects can obtain funding through the ecoENERGY fund, the Clean Energy Fund program and State Governments. As an example Canada’s Economic Action Plan invests $1 billion for clean energy research and demonstration projects, including $650 million for large-scale carbon capture and storage projects.

Australia’s CCS flagship program provides funding of AUS$1.68 billion for the demonstration of CCS in the electricity production including transport and storage issues.

Moreover, different approaches like the Asian Development Bank (ADB) CCS Trust Fund are aiming at the support of CCS demonstration in developing countries

The Norwegian government has granted 75% support to the Norcem pilot CCS project in Brevik, Norway. Different technology providers for post-combustion capture are expected to test their equipment at the plant.

In 2009, $3.4 billion have been designated for CCS programmes within the American Recovery and Reinvestment Act (ARRA) in the United States (cost sharing with industry). This funding was broken down into three major initiatives: for a competitive bidding for industrial CCS projects, for the Clean Coal Power Initiative (CCPI), and for FutureGen. There are 3 large scale industrial CCS demonstration projects (ethanol production, steam methane reformer, methanol) that have been selected by the U.S. Department of Energy (DOE) to receive funding for design, construction, and operation [MIT-13]. The three projects are expected to capture and store a total of 6.5 million tons of CO_2 per year in 2015. “Overall, within the United States, demonstration projects reliant on government support will continue to rely strongly on the run up in funding that culminated with the ARRA, rather than expect that future sources of funding will be made available.” [GCI-11] In any case, the release of funds is still pending.

To what degree funding of CCS pilot and demonstration projects can initiate demonstration projects remains to be seen. The biggest obstacles are certainly the costs involved and in particular operating costs which can under the current situations in most countries and regions cannot be passed on. In addition, the lack of appropriate storage sites limits the practicality to move ahead with demonstrations projects.

6.5 Conclusions and recommendations

In order to achieve the climate target of limiting the global temperature increase to 2°C carbon capture and storage technologies are seen as a key technology to reduce CO_2 emissions [IEA-09/2]. The European Union considers CCS technologies at least as bridging technologies in its CCS directive. The questionnaire amongst stakeholders of the cement industry underlined the potential of CCS technologies for future CO_2 reduction and the willingness to apply the technologies. However, many concerns, in particularly with regard to technical and economic feasibility, were expressed. Uncertainties originating from the current legal framework and political developments were named as barriers for the further development of CCS. Measures for CO_2 emission reduction are mainly seen in the further development of existing cements. New cements and binding materials are currently under development and largely in a research stage. Their application is not expected to significantly substitute Portland cement clinker in the near future. Notwithstanding the overall technical and economic barriers, at this time carbon capture seems to be (in particular due to its process CO_2 emissions) the only solution to achieve a near complete reduction in the CO_2 emissions from the cement industry.

To fulfill the UN CO_2 reduction target by 2050, which according to the IEA, implies that half of the cement plants operated in Europe, Northern America, Australia and East Asia would have to be equipped with CCS by 2050 [IEA-09/2], CCS would have had to be already demonstrated in the cement industry. However, none of the near-term actions for 2015 to 2020 as stated by the IEA in 2011 appear to be close to realisation [IEA-13/2]. As industrial pilot applications have only recently been initiated, post-combustion capture cannot be expected to be commercially applied to several plants, even with political and economic support implications, before 2020, and oxyfuel not before 2030.

This forecast presumes sufficient funding as an accelerator of technology development. “However, the policy drivers for gaining experience are lacking. Coalitions of willing governments and companies can valuably drive the development of these crucial technologies now to make them available for the coming decades” [IEA-13/2]. A jointly led technology demonstration programme could minimize the individual expenditures, as smaller cement companies could not bear the high economic risk involved. This includes the involvement of all stakeholders of the full chain, such as cement manufacturers, equipment suppliers (cement), gas suppliers, the technology provider (capture technology) and universities as well as the evaluation of synergies to other industry sectors. In the case of reusing the CO_2, potential consumers (using CO_2 as feedstock) could be involved at an early stage. “Funds could come from CO_2 certificate revenues or sectorial production levies, in addition to R&D budgets” [IEA-13/2].

Besides “Public funding for well-designed research and development projects, the necessary political developments, and open and transparent discussion with our stakeholders about the pros and cons of CCS will be required” [CEM-12]. But “deploying a pollution control method such as CCS requires policy action; it is not something that a market will deliver if left alone.” “Investments will flow where the sector has a confident outlook” [IEA-13/2]. Therefore, governments and groups of countries need to be aware of the cement market situation and the development within the industry to offer support by long-term policy.

Apart from the uncertainties about the technical feasibility, cement plant operators are concerned about the impact of CCS on their competitiveness. Since the costs for CCS and the corresponding CO_2 price are very high there is always a significant risk that clinker and/or cement are imported from countries with lower abatement costs with the corresponding carbon leakage. Furthermore, even if prices would increase as a consequence of changing political rules, the additional costs of emitting CO_2 would have to be borne by the operator until technical abatement measures like carbon capture would be implemented. This must be taken into account in designing the appropriate legal framework for CO_2 abatement to drive the deployment of low carbon technologies such as CCS. If this technology will be commercially available, policy instruments like financial penalties on poor energy performance or CO_2 emissions to fund incentives could enable investors to consider CCS as competitive [IEA-13/2].

In summary, the overall investment costs and the operational costs are seen as a significant barrier to initiate even the first steps towards pilot and demonstration plants. Any time frame for either one of the technologies will therefore to a large degree depend on substantial funding. However, currently there are no adequate funding programmes specialised for the cement industry available. Even more important, however, are the missing overall legal frameworks and the underdeveloped transport and storage infrastructure. There seems to be little incentive to undertake an extremely high cost project to build a CCS installation without a dedicated political approach which addresses the risk of carbon leakage and a clear perspective towards reliable storage options.

Against this background the reuse of CO_2 might provide a better outlet for captured CO_2 from cement plants. Power to gas projects, for example, have been initiated and might provide a good link between energy storage and CO_2 utilisation. To what extent such a combined technology will be technical and economical feasible, remains open at this time. First indicative studies outline the potential of such an approach but also underline the need for further research in this field.

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8 Annex

8.1 List of abbreviation

Table 8-1 List of abbreviation

Abbreviation	**Meaning**
A_0	Initial investment costs
C	Costs of avoided emissions
CHP	Combined heat and power
CCS	Carbon Capture and Storage
CCR	Carbon Capture and Reuse
cem	Cement
cli	Cement clinker
E	CO_2 emissions
EUA	European Allowances for CO_2 emissions (in €/t CO_2)
FTE	Full time employee
i	Discount rate
K	Capital charges
n	Economic plant life
NGCC	Natural gas combined cycle
NO_x	Nitrogen oxide
PC	Production costs
SCR	Selective catalytic reduction (for NO_x emissions)
SCNR	Selective non catalytic reduction (for NO_x emissions)
SO_x	sulphur oxide
TCR	Total capital required
TPC	Total plant costs

8.2 Source of assumption

Table 8-2 Basis of general assumption

Reference plant – general assumption		**Source**
Technology standard	BAT (calciner, 5-stage cyclone)	European BREF-Document
Location	Europe	Specifications IEAGHG
Production capacity	1 M t clinker/y	Agreement IEAGHG
Cement production	1.36 M t cement/y	(from GNR)
Clinker/cement factor	73.7 %	[GNR-10], EU 28
Raw meal/clinker factor	1.6	
Spec. fuel consumption	3,280 kJ/kg clinker	[Kle-06]
Fossil fuel	69.5 %	[GNR-10], EU 28
Alternative fuels	26 %	[GNR-10], EU 28
Biomass	4.5 %	[GNR-10], EU 28
Spec. total electricity consumption	97 kWh/t cement	[GNR-10], 20 percentile, all kilns, EU 28
Spec. electricity for clinker production	65 kWh/t clinker	Expertise ECRA
Raw material moisture	6 %	Assumption based on expertise ECRA
Reference plant – CO$_2$ emissions		
CO$_2$ from electricity	0.5 - 0.7 t CO$_2$/MWh	[CSI-09]
CO$_2$ from process (excl. electricity)	0.828 t CO$_2$/t clinker	According to scenario of [Kle-06]
Biogenic fraction of alternative fuels		
Animal meal	100 %	Expertise ECRA
Sewage sludge	100 %	Expertise ECRA
Communal wastes	50 %	Expertise ECRA
Plastics, textile, packaging	30 %	Expertise ECRA
Tyres	27 %	Expertise ECRA
Solvents, oil residues	0 %	Expertise ECRA
Emission limits		
SO$_2$, mg/Nm^3	50*	Industrial Emissions Directive
NO$_X$, mg/Nm^3	500**	Industrial Emissions Directive
C, mg/Nm^3	10*	Industrial Emissions Directive
Particulates, mg/Nm^3	30	Industrial Emissions Directive
Reference – cost related issues		
Total plant costs	170 M €	[CSI-09]
Total plant costs	170 €/t yearly prod.	[CSI-09]
Discount rate	8 %	Specifications IEAGHG
Operating costs	31.3 €/t clinker	Expertise ECRA
Plant life	25 y	Specifications IEAGHG
Coal price	80 €/t	European average in 2013
Alternative fuels	average 20 €/t	related to [McK-08] (15-30 % of coal price)
Power price	80 €/kWh	European average in 2013

BAT-Reference plant – general assumption		Source
Operating capacity	330 d/y	[CSI-09]
Insurance, taxes etc.	1 % of investment	Specifications IEAGHG

* Exemption depending on raw material possible

** Exemption for long and Lepol kilns to max. 800 mg/m$^3{}_{STP}$ until 01st Jan 2015 possible