Cement Sustainability Initiative (CSI), a member-led program of the World Business Council for Sustainable Development (WBCSD)

Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead

(CSI/ECRA-Technology Papers)

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european cement research academy

This study “Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead” was commissioned by the Cement Sustainability Initiative (CSI), a member-led program of the World Business Council for Sustainable Development (WBCSD). The report represents the independent research efforts of the European Cement Research Academy (ECRA) to identify, describe and evaluate 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. While the results have been reviewed by ECRA and CSI member companies and stakeholders like the International Energy Agency (IEA), the opinions and views expressed are those of ECRA.

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1 Introduction and objectives

In June 2008 the International Energy Agency published a report called Energy Technology Perspectives which contains the outlines of roadmaps for 70 industry sectors to achieve long-term CO_2 reduction targets. On request of the G8 leaders at the 2008 G8 Hokkaido summit the International Energy Agency has been asked to prepare more detailed roadmaps to advance key innovative energy technologies to achieve a 50% reduction of total global CO_2 emissions by 2050.

The roadmap for the cement industry shall identify major barriers, opportunities, and policy measures for policy makers, industry and financial partners in order to accelerate research and development of technologies aiming at increasing energy efficiency and reducing greenhouse gas emissions. The roadmaps shall be agreed by relevant stakeholders like industry, governments etc. Since autumn 2008, IEA is co-operating with the Cement Sustainability Initiative (CSI) in order to produce the technical basis for the cement roadmap. Therefore, CSI has offered to provide a documentation, so-called technology papers, which contain the description of energy saving and CO_2 reducing technologies, their costs in typical future cement plants, their energy saving and CO_2 reduction potentials, boundaries and limitations as well as the timeline for implementation. CSI has commissioned the European Cement Research Academy (ECRA) to propose a list of relevant technologies which shall be considered and to write the technologies papers.

The present report comprises 33 technology papers as well as 5 so-called state of the art papers. The state of the art-papers summarize the expected development in the major technological fields, which are thermal energy efficiency, electric energy efficiency, use of alternative fuels and biomass, reduction of the clinker content in cement, and CO_2 capture and storage. It has been agreed that estimations concerning the reduction potential and cost shall be related to two reference plants. Both plants shall have a clinker capacity of 2 million tonnes per year or 6,000 tonnes per day respectively. The CSI provided technical data from their GNR (Get the Numbers Right) project, in which data from 800 cement installations worldwide have been collected. The average data of all cement plants have been used to define the typical present cement plant. The 20% percentile data have been used to define the performance of a new installed cement plant. The key assumptions as well as the data of the reference plants are summarized in the annex of this report. All calculations and assumptions relate to these plants if not mentioned differently. Cost data relate to Central European prices and have to be adapted for other regions in the world, like China, India or Latin America*).

*) Extensive technology and cost information for Asia and the US have shortly been published in the APP booklet (http://www.asiapacificpartnership.org/cement_tf_technologies_booklet.aspx).

The estimations and information given for future years 2030 and 2050 are based on today's technical knowledge, assumptions for further development, literature and internet data as well as the knowledge available in the European Cement Research Academy.

Duesseldorf, 4 June 2009

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2 State of the Art-Papers

2.1 State of the Art-Paper No 1:

Thermal efficiency of cement production: state of the art and long-term perspective

2.1.1 Status 2006

Based on the GNR (CSI “Get the Numbers Right” data collection) data for the year 2006, the thermal energy consumption (as global weighted average) for cement clinker manufacturing was 3,690 MJ/t cli. This value covers more than 800 kilns worldwide, all technologies and clinker types. The variations are significant: the 10% best of class (10% percentile) relating to all kilns was ca. 3,100 MJ/t cli. On the other hand, the 90% percentile (90% of the kilns have been below this value) came up to ca. 4,400 MJ/t cli. Also the variations in the different regions of the world are significant. Highest energy consumption (up to more than 6,000 MJ/t cli) is required for the wet production process, while lowest values (down to 3,000 MJ/t cli) are achieved by state of the art precalciner kiln technology linked to large kiln capacity, low moisture content and good burnability of the raw materials. It has to be stressed that these data represent yearly averages whereas performance values are usually expressed as short-term (typically 24h- or 36h-average) values. Depending on kiln operation and reliability (e.g. number of kiln stops), market situation etc. there can be a difference of 150 to 300 MJ/t clinker between these levels.

As cement manufacturing is highly capital intensive, the lifetime of cement kilns is usually 30 to 50 years. Therefore, new kilns are therefore predominantly built in places where market growth is high – in the last decade mainly in Asia and some parts of Eastern Europe. On the other hand, the technical equipment of cement kilns is modernised continuously, meaning that often after 20 or 30 years most of the original equipment has been replaced (e.g. preheater cyclones, clinker cooler, burner etc.) and is always adapted to modern technology. This can be seen e.g. from the European data, where kilns are relatively old, but nevertheless efficient. Only huge retrofits like changing from wet to dry process allow a significant step in increasing energy efficiency. For this kind of retrofits similar investment as for new kilns is required. Therefore, they will only be carried out if the market situation is very promising or the equipment is already very old. By this kind of extensive retrofits it is often possible to largely close the efficiency gap to state of the art technology. On the other hand retrofits often have to take compromises into account, e.g. due to limited downtime of the kiln.

2.1.2 Thermal energy demand of the clinker production process

The thermal energy demand for clinker production is ruled by endothermic reactions of the raw materials with required temperatures of up to 1,450°C for the formation of stable clinker phases. Therefore, a theoretical energy demand of 1,650 to 1,800 MJ/t clinker is needed for this process. Depending on the moisture content of raw materials a further energy demand of about 200 to 1,000 MJ/t clinker (corresponding to a moisture content of 3 to 15%) is required for raw material drying. As a consequence, a theoretical minimum energy demand of 1,850 to 2,800 MJ/t clinker is set by chemical and mineralogical reactions and drying. Furthermore, waste heat (kiln exhaust gas, bypass gas and/ or cooler exhaust air) is often used for the drying of other materials like coal and petcoke or cement constituents like granulated blast furnace slag. Therefore, energy efficiency (expressed as dissipated energy related to energy input) of cement kilns is very high compared to many other industrial processes, especially compared to power plants. As a consequence, kilns with significantly different specific thermal energy consumption can be similarly efficient if waste heat utilisation for raw materials drying, electric power consumption, etc. is taken into account.

2.1.3 Criteria

Most important factors determining the specific fuel energy demand are:

- chemical characteristics of the raw materials
  (moisture content, chemical composition)
- mineralogical characteristics of raw material
  (raw material types of the respective storage site, burnability)
- production capacity of the plant
- technical status of the plant
- fuel properties, fuel mix and availability (caloric value, reactivity)
- kiln operation

The technologies and different impacts on energy efficiency as well as the measures to reduce it are described and assessed quantitatively (concerning reduction potential and costs) in the technology papers. **It has to be stressed that simply adding up the described reduction potentials of single measures in order to calculate total potentials is not feasible!** Firstly, some measures or technologies have interacting impacts. Secondly, it is not possible go beyond the minimum energy demand, meaning “that one kJ can only be reduced once”. Last but not least, many thermal energy reducing measures cause an increase of power consumption.

2.1.4 Expected development of state of the art-techniques

For the time being the dry process with precalcining technology is state of the art. Based on the GNR data the weighted average of the specific thermal energy consumption for this kiln type in 2006 was 3,382 MJ/t clinker. The respective value for 1990 was 3,605 MJ/t clinker, equivalent to a reduction of ca. 220 MJ/t clinker over 16 years. In this time period the average kiln capacity increased significantly. While in the beginning of the 1990´s max. kiln capacities of 5,000 to 6,000 tpd were typical, today max. capacities come up to 8,500 to >10,000 tpd. Such an increase cannot be expected to continue in the future. On the other hand, the average kiln capacity of cement plants will increase globally because new kilns are often built with high capacities (especially in growing markets) and existing smaller kilns will increasingly be replaced by bigger ones (in stagnant markets without increasing total capacity).

A study carried out by the Research Institute of the Cement Industry, Germany, in the context of the European BAT process has determined the ranges for the yearly average fuel energy requirement of state of the art cement kilns based on theoretical modelling and empirical data. These data take all criteria and impacts into account:

3 cyclone stages: 3,400 to 3,800 MJ/t clinker

4 cyclone stages: 3,200 to 3,600 MJ/t clinker

5 cyclone stages: 3,100 to 3,500 MJ/t clinker

6 cyclone stages: 3,000 to 3,400 MJ/t clinker

Break-through technologies which could lead to a significantly higher thermal efficiency are not in sight. The fluidised bed is an interesting process but this technology must yet prove its suitability. Furthermore, it is expected that it will probably not cover the segment of big kiln capacities.

Based on these assumptions the specific fuel energy demand of clinker burning (as a global weighted yearly average) may decrease from 3,690 MJ/t clinker in 2006 to a level of 3,300 to 3,400 MJ/t clinker in 2030 and to 3200 to 3,300 MJ/t clinker in 2050. However, without impairing efficiency these specific energy data can be higher if e.g. additional waste heat must be generated for the purpose of cogeneration of electric power. Similar considerations apply if Carbon Capture and Storage would have to be implemented. It is supposed that no wet, semi-wet, semi-dry or long dry kilns will be in operation anymore, except at those sites with wet raw materials.

2.2 State of the Art-Paper No 2:

Electric efficiency of cement production: state of the art and long-term perspective

2.2.1 Status 2006

Based on the GNR (CSI “Get the Numbers Right” data collection) data for the year 2006, the global average electric energy consumption for cement manufacturing was 111 kWh/t cement. This value covers more than 800 kilns worldwide, all technologies and clinker and cement types. The variations are significant: the 10% best of class (10% percentile) relating to all plants was ca. 89 kWh/t cement. On the other hand, the 90% percentile (90% of the plants were below this value) came up to ca. 130 kWh/t cement. The variations in the different regions of the world are also significant. It has to be stressed that these data represent yearly averages whereas performance values are usually expressed as short-term (typically 24h- or 36h-average) values. Depending on plant operation and reliability (e.g. number of kiln or mill stops), market situation etc. there can be a significant difference between these levels.

As cement manufacturing is highly capital intensive, the lifetime of cement plants is usually 30 to 50 years. However, new equipment is not only found in places where capacities have been built up due to high market growth (in the last decade mainly in Asia and some parts of Eastern Europe); typically the technical equipment of existing cement plants is modernized continuously, meaning that often after 20 or 30 years most of the original equipment has been replaced (e.g. preheater cyclones, clinker cooler, separators etc.) and is always adapted to modern technology. But a significant decrease in specific power consumption is only achieved through huge retrofits like changing from cement grinding with ball mills (BM) to high efficient vertical roller mills (VRM) or high pressure grinding rolls (HPGR). For this kind of retrofits high investment is required. Therefore, they will only be carried out if the market situation is very promising or the equipment already very old.

2.2.2 Electric energy demand of the cement production process

Concerning the dry process the total power consumption can be assigned to about 5 % for raw material extraction and blending, 24 % for raw material grinding, 6% for raw material homogenisation, 22% for clinker production (incl. solid fuels grinding), 38 % for cement grinding and 5% for conveying, packing and loading.

As grinding processes consume most of the power, grinding technology has a major impact on total electric energy demand: cement plants which use modern grinding technologies – e.g. high pressure grinding rolls (HPGR) and vertical roller mills (VRM) for raw material and cement comminution instead of ball mills (BM) usually have a lower energy consumption. However this has to be seen against the background of cement quality which depends on the type of mill.

Concerning the clinker burning process, measures which increase thermal efficiency often need more electric power. For example, the installation of modern grate cooler technique causes a reduction of thermal energy use, but increases the consumption of electrical energy. On the other hand, changing from long wet kiln technology to modern dry process kiln precalciner saves theoretically up to 5 kWh/t clinker.

Specific power consumption has increased in many countries in the past, because environmental requirements have increased. Lower dust emission limit values require more power for dust separation regardless of which technology is applied. The abatement of other constituents (like NO_x or SO_2) might require additional units which require electricity.

Cement performance has an important impact on power consumption. For example, the higher a cement's strength development, the finer it typically has to be ground, requiring significantly higher power consumption.

2.2.3 Criteria

Most important factors determining the specific electric energy demand are:

- installed grinding and separator technology for raw material comminution and cement production
- intended cement quality/product portfolio
- environmental standards
- technical status of the plant
- plant operation

The technologies and different impacts on energy efficiency as well as the measures to reduce it are described and assessed quantitatively (concerning reduction potential and costs) in the technology papers. It has to be stressed that simply adding up the described reduction potentials of single measures in order to calculate total potentials is not feasible! It is not possible to go beyond the minimum energy demand, meaning "that one kWh can only be reduced once". And – as already mentioned - many thermal energy reducing measures cause an increase in power consumption.

2.2.4 Expected development of state of the art-techniques

For the time being the grinding with HPGR and VRM, if need be in combination with ball mill for cement finish grinding, is state of the art. Based on the GNR data the global weighted average of the specific thermal energy consumption for all participating companies has been reduced from 115 kWh/t cement in 1990 to 111 kWh in 2006, corresponding to a reduction of ca. 4 kWh/t cement over 16 years. This comparatively small reduction in the given time period indicates that there have been developments that required additional electrical energy and therefore prevented a stronger decrease in power consumption.

From theory it can be expected that single particle grinding requires much less energy than todays grinding equipment. However, bulk grinding still limits the focussing of the grinding forces to single particles and consequently no breakthrough technologies are in sight today. A fundamental change in the actual cement producing technology, causing from today's perspective a significant reduction in the specific energy consumption is unlikely.

On the other hand it can be expected that environmental requirements will increase and that the cement manufacturing process therefore will have to be enlarged by more and more units, ending up in a significant increase in power consumption. The most electricity intensive technologies which are discussed for future implementation possibly also in the cement industry are carbon capture technologies.

Based on these assumptions without CCS the specific electric energy demand of cement production (as a global weighted yearly average) may decrease from 110 kWh/t cement in 2006 to a level of about 105 kWh/t cement in 2030 and to 95 to 100 kWh/t cement in 2050.

If CCS is applied on big scale, power consumption of cement manufacturing will increase significantly! As described in the respective technology papers, oxy-fuel as well as post combustion technologies will require high power consumption for oxygen production by air separation, regeneration of absorbent agents as well as for separation, purification and compression of CO_2. Therefore CCS would increase power consumption by 50 to 120% on plant level. Assuming a high implementation degree of max. 20% of cement capacity in 2030 and up to 40% in 2050 (see BAT paper 5 on CCS) a power demand of cement production (as global average) of 115 to 130 kWh/t cement is expected in 2030 and 115 to 145 kWh/t cement for 2050.

2.3 State of the Art-Paper No 3:

Alternative fuels and biomass use in the cement industry: long-term perspective

2.3.1 Status 2006

Based on the GNR (CSI "Get the Numbers Right" data collection) data for the year 2006, the use of alternative fuels on a global level was 7% in relation to the total fuel energy consumption for cement manufacturing. Almost 3% was covered by biomass and the remaining 90% was provided by conventional fuels, mainly coal. The variations on a global level in the different regions were significant: the 10% best of class (90% percentile) covering all kilns came up to substitution rate of 23% for alternative fuels and 10% for biomass, respectively. From a technical point of view, much higher substitution rates are possible. This can be demonstrated from experiences in some European countries, where the average substitution rate reaches more than 50% for an industry sector and up to 80% as yearly average for single cement plants. As the fuel-related CO_2 emissions are about one third of the total emissions (325 of 866 kg CO_2 per tonne of clinker for the reference plant), the CO_2 reduction potential can be significant if pure biomass use is assumed. Beneath direct effects, the use of waste as alternative fuel in cement kilns may contribute to lower overall CO_2 emissions, replacing fossil fuels and their relevant CO_2 emissions with waste materials, which would otherwise have to be incinerated or land filled with corresponding greenhouse gas emissions. Emissions from landfill consist of about 60% methane, a gas with a global warming potential 21 times that of CO_2. The extent of this effect strongly depends on the waste properties and the local conditions of waste treatment.

2.3.2 Fuel types

The CO_2 reduction potential of alternative fuels containing biomass is principally based on two direct effects: first, many alternative fuels exhibit a certain biomass content of which the CO_2 emission factor is accounted zero. Second, most fossil alternative fuels have lower CO_2 emission factors related to its calorific value than coal or petcoke. Above that, there can be an indirect effect of emissions reduced outside the cement plant if wastes are used there instead of land filling or incinerating them in separate installations. Typical alternative fuels classified as wastes are waste tyres, waste oil and solvents, pretreated industrial and domestic wastes, plastic, textile and paper wastes etc. Pure biomass fuels used in the cement industry today are mainly animal meal, waste wood, sawdust and sewage sludge. Besides these fuels, many other organic waste materials are used as fuels in the cement industry globally, however to a smaller extent. Fuels containing biomass are mainly pre-treated industrial and domestic wastes (containing certain parts of organic fibres and textiles, paper, etc.). Principally, it is also possible to use other organic material as fuels, like natural wood or certain grass types (e.g. miscanthus), other quickly-growing species or cultivated green algae. These materials are no wastes and have to be cropped especially for the later use as fuels. Today this is not relevant for the cement industry globally for economic reasons.

2.3.3 Criteria

- Principally, cement kilns can utilize up to 100% of alternative fuels. Nevertheless, there are certain technical limitations like the calorific value, and the content of side products like trace elements or chlorine. The calorific value of most organic material is comparatively low (10 – 18 GJ/t). For the main firing of the cement kiln an average calorific value of at least 20-22 GJ/t is required. In the precalciner of modern cement kilns, in which up to 60 % of the fuel input is realised, the lower process temperature allows also the use of low calorific fuels. Therefore, precalciner kilns are able to burn at least 60% of low calorific fuels. A lower calorific value as well as high-chlorine content (requiring a chlorine by-pass system) will increase the specific fuel energy consumption per tonne of clinker. Therefore it is possible that although the use of those fuels leads to lower energy efficiency, CO_2 emissions are reduced nevertheless.
- As cement kilns operate significantly different if high percentage of conventional fuels are substituted by alternative fuels, the penetration of technical operational experiences within the cement industry are a major criterion for the use of such fuels on a global level.
- Higher replacement rates of fossil fuels by alternative fuels will only take place if the waste legislation in the given region restricts land filling and allows a controlled waste collection, treatment and alternative fuel production.
- The social acceptance of using wastes as alternative fuels in cement plants is of huge relevance.
- Concerning the use of separately grown biomass crops, the availability of agricultural areas, especially in densely inhabited regions, is of huge relevance.
- CO_2 legislation will have a significant impact on the available quantities of waste and biomass fuels which will be available for the cement industry.
- Due to high CO_2 costs it can be expected that prices for alternative fuels will increasingly depend on the biomass content. This will encourage the separate planting of so-called cash crops for use in various industrial sectors. However, if power production from biogenic materials is subsidised by legislation, it will be to a growing extent be more difficult for the cement industry to receive significant quantities of these materials at acceptable prices.

2.3.4 Expected market development

Today in Europe many alternative fuels have lower or even negative prices compared to conventional fuels. As a principle, the higher the calorific value and the lower the content of other elements such as chlorine in particular is, the higher the fuel price. In the future it can be expected that prices for alternative fuels and especially for biomass will increase significantly. In the attached technology papers it is assumed that alternative fuel prices will rise up to about 30% of conventional fuel costs in 2030 and 70% in 2050. Before that time, it is expected that there will still be an economic benefit for cement plant operators to utilize alternative fuels, especially fuels containing biomass, but the payback time may become much longer compared to today. Of course this development will be significantly influenced by CO_2 prices.

2.3.5 Development of state of the art-techniques

Due to the large number of technical, economic and political/societal criteria described above, it is very difficult to predict “state of the art”-values for future substitution of conventional fuels by waste or biomass fuels. It has to be stressed that the achievement of these values have stronger political and legal aspects than technical ones. Nevertheless, a precautious estimation points to the possibility that in developing regions the substitution rate can rise up to 10-20% in 2030, whereas in developed regions a substitution rate on the industrial sector level of 50-60% should be possible. Globally this could lead to a level of about 30% as an average. In 2050 the estimations predict a substitution of 20-30% in developing regions and 50-60% in developed regions, corresponding to about 35% on a global level. This development can only be achieved if on a global level significant changes in waste legislation, waste collection and preparation technologies and in social acceptance of waste-incineration cement plants are implemented. Furthermore, it has to be assured that sufficient quantities of required materials are available for the cement industry.

2.4 State of the Art-Paper No 4:

Reduction of clinker content in cement: long-term perspective

2.4.1 Status 2006

Based on the GNR (CSI "Get the Numbers Right" data collection) data for the year 2006, the clinker-to-cement ratio on global level was 78% (as weighted average, company level). Based on a total cement production of about 2,400 mio. tonnes this was equivalent to the use of more than 400 mio. t of clinker substituting materials. The variations of the clinker-to-cement-ratio in the different world regions were significant in 2006: The 10% best of class (10% percentile) of all companies covered by the GNR showed a clinker-to-cement ratio of 68%, whereas the 90% percentile was nearly 90%. In Europe, for example, the weighted average was 75%, the 10% percentile of the clinker-to-cement ratio being 63%. From a technical point of view, lower weighted average values are possible. Materials like blast furnace slag, fly ash, natural pozzolanas or lime stone meal are available globally in respective quantities; however, regional availability is very different and limits the use of such materials.

2.4.2 Materials which can substitute clinker in cement

Cements that contain other constituents besides clinker exhibit a lower clinker-to-cement-ratio than Portland cement and consequently show less energy demand for the clinker burning as well as less process CO_2 emissions due to the decarbonation of the limestone. The other cement constituents show hydraulic and/or pozzolanic activity or filler properties and contribute positively to the cement performance.

- Granulated blast furnace slag (GBFS): Molten iron slag is a by-product of the pig-iron production process and can be quenched in water or steam. The glassy, granular product, granulated blast furnace slag (GBFS), shows latent hydraulic behaviour, i.e. its hydraulicity must be activated e.g. by calcium hydroxide that is formed by the hydration of clinker. As this reaction is slower than the clinker hydration, cements containing GBFS usually show a lower early strength if ground to the same fineness and a lower heat of hydration. These cements often show higher long term strength and particularly improved chemical resistance.
- Fly ash (FA): Fly ash is obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases from furnaces fired with pulverised coal. FA may be siliceous or calcareous in nature and has pozzolanic properties (calcareous FA may have some hydraulic properties besides the pozzolanic properties). Since the reaction of pozzolanic material is slower than that of clinker, cements containing FA typically show a lower early strength compared to ordinary Portland cement (OPC) at similar fineness. They also exhibit a lower water demand, an improved workability, a higher long-term strength and - depending on the application - a better durability such as an increased resistance against sulfate attack.
- Pozzolanas: Natural pozzolanas are usually materials of volcanic origin or sedimentary rocks with suitable chemical and mineralogical composition. Natural calcined pozzolanas

are 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. Sililca fume, a byproduct in the production of silicon an ferro-silicon alloys, is a very effective puzzolanic material because of its extreme fineness and its high silica content. However, its worldwide availability is limited. Pozzolanas contain siliceous or silico-aluminous phases which can react in cement paste and contribute to strength-development. Similar to FA-containing cements and compared to Portland cement, the early strength of pozzolana-containing cements decreases with increasing proportion of pozzolana; they show a better workability, a higher long-term strength and particularly an improved chemical resistance.

- Limestone: the use of limestone as a minor or main constituent in cement is an efficient method to reduce the clinker/cement ratio of cement. However, limestone does not contribute to the strength formation of the hardening cement paste. If limestone-containing cements are adjusted to give the same strength as OPC they have to be ground to a higher fineness. The amount of limestone in cement and its quantity are decisive for the resistance of the hardened paste to acids and sulphates and its freeze-thaw-resistance. Typically limestone leads to a better workability of the concrete.

2.4.3 Criteria

The use of other constituents in cement besides clinker depends on six criteria: Availability, properties and prices of the materials as well as intended application of the cement, national standards and market acceptance. The regional availability of clinker-replacing materials varies considerably. For example, the availability of GBFS depends on the locations and output of blast furnaces for pig-iron production. Actually, an estimated 200 mio. t/a GBFS are produced worldwide. Fly ash is produced in coal fired power plants; the actual worldwide production is estimated to 500 mio. t/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 very difficult to predict. In 2003 estimated 30 mio. t natural pozzolana were available worldwide, but only about 50% were used in cement and concrete industries. The availability of pozzolana depends on the local situation and clearly shows only a very limited number of regions providing this material for cement production. Limestone is easily available for most cement plants, and the worldwide availability will not be limited within the next few hundred years. The properties of the constituent besides clinker are very important and always have to be assessed with respect to the intended application of the cement. For example, from a cement standard point of view blastfurnace cements can contain up to 80 or even 95% of GBFS. However, due to its low strength development these cements are only suitable for very special applications. In any case, all cement constituents must comply with certain qualities like those given in the standards; otherwise the quality and performance of corresponding mortars or concretes might be significantly impaired. In summary the use of cements containing more constituents than clinker must always take into account the requirements from an application point of view. In this context an increased use of such cements in mortar or concrete must always be safeguarded through good durability and workability, appropriate strength development and sufficient resistance against aggressive media if required. This would also imply that national standards and rules have to be revised accordingly. The market acceptance will strongly depend on the performance of cements with lower clinker-to-cement-ratio and requires cement producers and cement users to introduce these cements to the market in a joint effort. The prices of clinker reducing materials depend on the local situation. An increased demand and/or competition of different applications (e.g. cement, concrete, others) can lead to a rise in prices.

2.4.4 Expected development

The current availability of GBFS, FA, and pozzolana is estimated to be about 800 mio. t/a [*)], while the cement consumption is more than 2400 mio. t/a, with a significant further increase expected. (IEA has published that the availability of clinker substitutes including gypsum has been 1215 mio. tonnes in 2005.) A clinker-to-cement-ratio of 78% (2006, based on GNR) means that about 550 to 600 mio. t of substituting materials have been used globally (including limestone). This shows that an additional replacing potential exists: if 100% of substituting materials were to be used, the clinker content in cement could decrease to a minimum of about 60% on a global average. However, this scenario is rather theoretical because it does not take into account that quantities of these materials do not exhibit the required quality even today.

For a future scenario, it is assumed that the availability of slag, fly ash and pozzolana will increase at the same rate as cement consumption (no detailed information is available concerning this hypothesis). Limestone is available practically unlimitedly. It has to be considered that in some countries, e.g. in China, the US and in several European countries, clinker-substituting materials are used in notable amounts for other purposes like concrete production instead of cement production. Under these conditions it can be estimated that until 2030 the clinker-to-cement-ratio might be 70 to 75% and 65 to 70% in 2050. For this scenario, larger transportation distances will be required, which will lead to additional costs, energy consumption and CO_2 emission for the transport. The described interrelations show that the mentioned “classical” clinker-reducing cement constituents have a significant, but limited potential for the reduction of CO_2 emissions. The role of new types of cements/binders is still open. The availability of starting materials is not clear and current research shows only limited potential for mass production.

[*)] according to: Joachim Harder: Development of clinker substitutes in the cement industry, ZKG International 59 (2006), H. 2, P 58-64

2.5 State of the Art-Paper No 5:

Carbon Capture and Storage: long-term perspective for its application in the cement industry

2.5.1 Discussed technologies

CO_2 capture and storage (CCS) is an emerging approach for CO_2 abatement, which means that CO_2 arising from combustion processes and from process industries would be captured and stored away from the atmosphere for a very long period of time. After the power sector, cement production is one of the key emission sources. Therefore, CCS measures for potential CO_2 mitigation are also being discussed in the cement industry. Up to now, no results from pilot trials or industrial scale trials at rotary cement kilns are available - only several feasibility studies have been carried out. Besides technical aspects the economic framework will be decisive for future applications of carbon capture in the cement industry. At the moment, the costs for CO_2 capture amount from > 20 to > 75 €/ton CO_2 avoided. However, it is expected that the cost will decrease in the future according to the technical and scientific progress.

Today, all capture technologies are far away from being applicable to the clinker burning process. However, some capture technologies seem to be more appropriate for the potential application at cement kilns than others:

Post-combustion capture is an end-of-pipe measure and wouldn't require fundamental changes in the clinker burning process. Therefore this technology would be available not only for new kilns, but also for retrofits at existing cement kilns. The most promising post-combustion technology is chemical absorption because there are operational experiences from several industries and high abatement efficiencies seem to be achievable. In the long run, membrane technologies could also be a candidate for future application at cement kilns. Other post-combustion measures, e.g. physical absorption or mineral adsorption seem to be less feasible from today's point of view (because of a lack of selectivity or huge mass streams of mineral adsorbents). The carbonate looping process could be an interesting option for CO_2 capture too. Besides, synergies with power plants can be generated if the deactivated absorbent could be utilised as secondary raw material in the clinker burning process. However, the stage of development is low and basic R&D has to be carried out in the next years.

Oxy-fuel technology is a candidate for CO_2 capture at cement kilns as well. The use of oxygen instead of air in cement kilns would result in a comparatively pure CO_2 stream, which could be supplied to the transport and storage infrastructure. There are experiences from cement kilns in the USA which were operated with oxygen enrichment (to increase the production capacity). Furthermore, oxy-fuel technology will be investigated at power plants in the next years, so that some of the results obtained may be transferred to cement kilns. Nevertheless there is a need for extensive research activities to investigate all the potential impacts on the clinker burning process. Oxy-fuel combustion seems to be applicable especially at new kilns, because a retrofit at existing kilns would be very costly. An IEA supported study proposed a retrofit option in which only the precalciner of a cement kiln is operated in oxy-fuel mode. The other installations (kiln, cooler, raw mill) are operated conventionally. This option has the advantage of not necessitating high efforts in improvement of seals and of not having any impacts on the product quality. On the other hand, capture efficiency is lower (around 60%) compared to full oxyfuel operation of the clinker burning process (>85%).

Pre-combustion technologies are aiming to produce fuels which are more or less carbon-free (by a reforming or gasification process). 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 raw material) would be reduced. Furthermore, pre-combustion technologies would require significant changes of the combustion process (H2 as fuel). Therefore it can be excluded as potential capture technology for the cement industry.

Transport and storage of huge amounts of CO_2 is still an open question. From the point of technology and social acceptance this is a common challenge for all CO_2 emitting industries. It is open if a long term use of CO_2 besides storage is possible. Research on CO_2 decomposition by photosynthesis (e.g. with algae) or photo-catalytic reduction of CO_2 has been initiated but is today still in a preliminary state.

2.5.2 Criteria

- CO_2 capture technologies can only be realised, when the full chain of CCS is available, e.g.
- a transport infrastructure (pipeline network)
- access to suitable storage sites.
- The legal requirements for CO_2 transport and storage, monitoring and verification and for the licensing procedures have to be settled.
- Public acceptance must be ensured.
- Technology must be available on an industrial scale
- Economics and political conditions must allow the implementation of CCS in the cement industry without the possibility of carbon leakage.

2.5.3 Expected development

Up to now, no pilot trials or industrial scale trials at rotary cement kilns have been carried out - only several feasibility studies are available. From a technical point of view carbon capture technologies will probably not be available for the cement industry before 2020. It can be expected that in this period first research or pilot tests will be performed in order to gain first practical experiences with these new technologies. First demonstration projects are discussed already today, but nothing is decided so far. Therefore, it is principally possible that one or two demonstrations will be initiated until 2015. In the medium-term it is assumed that between 2020 and 2030 further full-scale demonstration projects will be initiated. Total CO_2 reduction will still be low. A rough estimation, based on 10 to 20 projects globally at rather big kilns (average 6000 tpd or 2 mio. t/a) and a reduction efficiency of 80% would lead to an overall reduction of max. 0.025 Gt/a. After 2030 CCS could become commercially implemented if the political framework supports it and social acceptance can be achieved, leading to significantly higher abatement rates.

A basic scenario postulates that the political framework will not impose similar carbon constraints for the cement industry on global level and therefore will allow a shift of production into countries or regions with less carbon constraints. Consequently, due to the very high costs, CCS will only be able to be applied in the cement industry if the political framework effectively limits the risk of carbon leakage. As CCS requires a CO_2 transport infrastructure and access to storage sites, cement kilns in industrialized regions could be connected to the grid while plants not in such areas will probably not have access. Though a lot of research is carried out aiming at exploring CO_2 storage sites and capacities worldwide, the technical availability of storage sites on global level is yet unknown. Therefore, an estimation of possible implementation is very difficult. In a scenario in which a share of 30% of the total cement kiln capacity is being built or operated in regions accessible to storage sites, CCS implementation in the cement industry would realistically not cover significantly more than 10 to 15% of the global clinker production capacity in 2050.

A scenario in which a global political framework covers a big share of global cement production, carbon leakage will be more or less prevented and CCS implementation could be significantly higher (provided that the open technical questions are solved). Due to higher specific costs, it is expected that kilns with a capacity of less than 4000 – 5000 tpd will not be equipped with CCS technology. Furthermore, new kilns will be equipped with this technology to a larger extent than existing ones (retrofits). Assuming a lifetime of a cement kiln of 30 to 50 years, 20 to 33% of the existing kilns will be replaced by new ones within 10 years. Assuming a share of big kilns on new capacity of 50% in the future and a (hardly realistic) implementation rate of 100% for new big kilns, between 2030 and 2050 a max. capacity share of 20 to 33% of the global capacity could be equipped with CCS. In addition, another 10% of existing kiln capacity could be equipped with end of the pipe technologies (post combustion). This means that CCS implementation will probably mainly take place in world regions where large new capacities are needed or where large kilns are in operation and could be retrofitted and where access to suitable storage sites is given.

3 Technology Papers

3.1 Technology Paper No 1: Improve raw mix burnability e.g. by mineralizers

Certain constituents which are contained in the raw material or are added to the raw material mix to promote clinker formation can have an important influence on the burning behaviour. Certain substances act as fluxing agents, i.e. even in small quantities they lower the viscosity of the melt at the same temperature. They generally also lower the temperature at which the clinker melt begins to form.
Mineralizers are substances which promote the formation of clinker compounds without participating in the formation reactions. It is not usually possible to differentiate between them as many substances act both as mineralizers and fluxing agents. Fluorides are particularly effective. They strongly promote the formation of tricalcium silicate and reduce the lower temperature limit of the C_3S stability range.
The fuel energy demand is reduced if the sintering zone temperature needed for clinker formation is lowered, e.g. by using mineralizers. For a modern kiln it has been estimated from model calculations that a reduction in sintering temperature by 200 K would result in a saving of fuel energy of up to 5%. Fluoride contents of up to 1% by mass of F- in the kiln feed do not alter the composition of the cement clinker but do promote clinker formation, with the result that the sintering temperature is lowered e.g. by about 150 K. The saving potential of this measure is limited, because, though addition of small quantities of mineralizers can improve product quality, larger quantities affect quality and kiln operation (increased coating formation). Additional costs by the mineralising or fluxing agents have to be considered. Especially CaF_2, which is used mostly is usually so costly, that fuel saving does not balance the additional costs. If mineral wastes containing fluoride are used costs can be negative. But availability of these materials is limited.

<u>Impact on energy consumption:</u>

thermal: decrease 50 to 180 [MJ/t cli]	electric: increase 0 to 1 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: 5 to 16 [kg CO_2/t cli]	indirect: increase 0 to 1 [kg CO_2/t cli]

<u>The main influencing parameters for the burnability are:</u>

- Chemical properties of the raw mix and mineralisers
- Mineralogy of its component materials and its fineness
- Raw mix control and kiln feed homogenisation
- CO_2 intensity of fuel mix

Cost estimation: (Operational costs: saved fuel costs and contained mill energy cost)

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015				0.06 to 0.43 de-crease
2030				0.06 to 0.43 decrease
2050				0.06 to 0.43 decrease

Remarks: Operation costs include fuel saving and additional power consumption. Market price for mineralizers has not been determined. Negative costs of fluoride containing wastes have not been taken into account. Usually no significant investment is required.

Conditions, barriers, constraints:

- Costs of mineralisers can be the key factor. In countries with abundant resources of fluoride the use of mineralizers can be less expensive.
- Grindability of clinker can deteriorate.
- Increased coating formation in the sintering zone is possible.
- Impact on clinker quality is possible.
- Impact on kiln operation and product properties are possible.
- It is unclear whether fluor emissions of the kiln and health problems increase, for example in some brick kilns and fired power plants.

3.2 Technology Paper No 2: Change from long kilns to preheater/precalciner kilns

The dry process with cyclone preheaters and precalciners is the state of the art technology for cement clinker production. Nevertheless, still many long dry or long wet kilns exist worldwide which are being replaced over time. The preheater technique with 3 to 6 cyclone stages improves – compared to long dry and wet kilns – the calcining efficiency by drying and preheating the raw material using the kiln exhaust gas.

Long wet and long dry kilns without preheater or precalciner have comparatively high energy consumption up to 6,000 MJ/t clinker on average for the long wet kiln. A retrofit of a long dry kiln to a multi-stage preheater or a kiln with precalcining technique is a feasible, but expensive measure for reducing energy consumption.

Energy savings depend strongly on the specific energy consumption of the long wet or dry kiln as well as the number of cyclone stages to be installed if retrofitted. Energy savings are estimated in a range of 900 MJ/t for a long dry kiln and up to 2,800 MJ/t clinker for a long wet kiln based on that of a modern preheater / precalciner and a modern clinker cooler. The throughput can be increased up to the double, or even more, of the long kiln production within the limits of the existing kiln size by installing a new preheater due to an extended degree of precalcination of the raw meal before entering the kiln inlet. In addition the kiln length may be shortened thereby reducing radiation losses, refractory and stress of the kiln shell through torsion. The conversion of such described old kiln types may become attractive in case that a new kiln line is too expensive. Furthermore, modern precalciner kilns show higher flexibility in using different types of alternative fuels.

The cost of converting a wet plant to a dry process plant may be very high, as it involves the full reconstruction of an existing facility. In any case wet raw material preparation can still be required depending on the type of raw material (e.g. chalk) even if preheater with cyclones is installed, forming a so-called ”semi-dry” system with integral dryer crusher.

This of course limits the energy saving potential significantly.

<u>Impact on energy consumption:</u>

thermal: decrease 900 to 2,800 [MJ/t cli]   electric: decrease 0 to 5 [kWh/t cli]

<u>CO_2 reduction potential</u>:

direct: 80 to 250 [kg CO_2/t cli]   indirect: decrease 0 to 3.5 [kg CO_2/t cli]

The main influencing parameters are:

- Initial specific fuel energy consumption of the long kiln
- Life cycle of the quarry
- Raw material humidity / number of cyclone stages
- Throughput capacity
- CO_2 intensity of alternative fuels
- CO_2 intensity of external power consumption

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015			70 to 100	2.85 to 9.2 decrease
2030			70 to 100	2.90 to 9.4 decrease
2050			70 to 100	3.00 to 9.6 decrease

Remarks: The cost estimation can't be based on a clinker capacity of 2 mio. t/a (6,000 tons per day), because long dry and wet kilns with that capacity don't exist. Therefore the investment cost given in the table are only indicative and for smaller capacity. Investment cost can be significantly higher depending on local conditions as well as extent of further plant modifications. The mentioned operating cost includes only fuel and power savings. Power saving can be less if raw materials with very good grindability (e.g. chalk) are used.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Very high investment cost incur with this measure
- Economics are ruled by power price/CO_2 price
- Clinker cooler technology / capacity is depending on increase of throughput capacity
- Economics can be improved by replacing primary fuels through secondary fuels

3.3 Technology Paper No 3: Preheater modification (e.g. cyclones with lower pressure drop)

Multi stage cyclone preheaters are main components for heat exchange of raw gas and raw meal in the clinker burning process. As there are at least 3 up to 6 cyclone stages based on the moisture content in the raw material the pressure loss of the whole preheater increases with the number of cyclone stages. State of the art cyclones with lower pressure drop reduce the power consumption of the exhaust gas fan system. Low pressure drop will be achieved by geometrical optimisation of the cyclone with nearly constant separation of the kiln meal. For each hPa of pressure loss reduction 0.12 – 0.15 kWh per ton clinker from electric energy can be saved, which is depending on the efficiency of the fan. For most existing kilns of older type this amounts to savings of 0.6-1.5 kWh per ton clinker. Replacement through low pressure drop cyclones can be economically reasonable when foundation and tower of the preheater are usable without rebuilding. In practise, the pressure drop is often balanced by higher air volume flow for increase of kiln capacity. The costs of such refurbishment are very site specific.

<u>Impact on energy consumption</u>:

thermal: [MJ/t cli]

electric: decrease 0.6 to 1.5 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: [kg CO_2/t cli]

indirect: 0 to 1 [kg CO_2/t cli]

<u>The main influencing parameters are:</u>

- Efficiency and volume flow of the ID fan
- Need for extra capacity
- Temperature/number of cyclone stages
- Pressure drop and efficiency of existing cyclone stages
- Power price
- CO_2 intensity of (external) power generation

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015			8 to 10	0.05 to 0.08 decrease
2030			8 to 10	0.05 to 0.08 decrease
2050			8 to 10	0.05 to 0.08 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a (6,000 tons per day), constant specific costs over time. Invest costs include the replacement of 3

cyclone stages (double string preheater). Impact on operation costs include saving of electricity costs.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Rework is depending on situation of basement and tower of the preheater
- Use of exhaust gas fans with adjustable speed drives may optimise process

3.4 Technology Paper No 4: Efficient clinker cooler technology

In cement production the energy of the hot clinker leaving the cement kiln is cooled in the clinker cooler while the clinker enthalpy is used for heating up the combustion air. Main clinker cooler technologies are the grate cooler, the planetary (or satellite) cooler and the rotary cooler. Planetary and rotary coolers use exactly the amount of air for clinker cooling which is needed for combustion. This leads to higher clinker end temperatures (between 120 to 200°C above ambient temperature) compared to grate coolers (down to 60 to 80°C above ambient temperature). Grate coolers use an excess of cooling air and therefore produce lower clinker outlet temperatures (down to 80 °C above ambient temperature). A stream of a cooler exhaust air is also produced and emitted, used for drying purposes or for power generation. Important advantages of grate coolers compared to planetary or rotary coolers are

- the larger capacity (up to 12,000 tpd) compared to max. 4,000 tpd
- the more efficient heat recovery.

In principle, planetary and rotary coolers can be replaced by grate coolers. Usually, this is only economically viable if the retrofit is linked with a change to precalciner technology and a significant capacity increase. Compared to 2nd generation or travelling grate coolers, modern reciprocating grate coolers (so-called 3rd generation) can be operated with extended lifetime and less heat losses. Grate coolers (and rotary coolers) can provide precalciners with preheated tertiary air. Modern reciprocating coolers can have a high degree of heat recuperation efficiency of 70 - 75%. Existing (2nd generation) grate coolers - with a typical efficiency of 50 – 65% - can be optimised by replacing the grate plates by more efficient plates, by adding a static first grate and – depending on the cooler type – a modified aeration system. Depending on the age of the cooler it can make more sense to replace the cooler completely.

Compared to planetary or rotary coolers, grate coolers require an extra power consumption of approximately 3 to 6 kWh/ t clinker. Fuel savings in the kiln are estimated to be up to 8%. The cost for the conversion from a planetary cooler to an efficient reciprocating grate cooler of newest generation with a capacity of 6,000 tons per day is estimated to 15 - 20 mio. €. These 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 retrofit of an old grate cooler demands an investment of 1 – 3 mio. €.

<u>Impact on energy consumption:</u>

thermal: decrease 100 to 300 [MJ/t cli]   electric: increase 1 to 6 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: decrease 9 to 28 [kg CO_2/t cli]   indirect: increase 1 to 3 [kg CO_2/t cli]

The main influencing parameters are:

- Clinker production rate
- Requirement of tertiary air for modern precalciner (e.g. combined with capacity increase)
- Degree of efficiency of existing cooler type
- Fuel mix
- Requirement of higher secondary air temperature, e.g. to improve secondary fuel combustion
- Amount of leak air
- Clinker temperature at cooler outlet

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015			1 to 3 15 to 20 (complete replacement)	0 to 0.5 decrease
2030			1 to 3 15 to 20 (complete replacement)	0 to 0.5 decrease
2050			1 to 3 15 to 20 (complete replacement)	0 to 0.5 decrease

Remarks: Operational cost includes fuel cost saving and additional cost for electric power. Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Economics may not be viable because market situation does not allow capacity increase
- Waste heat should be available for drying, heat recovery or power generation when necessary
- Economics are more viable at high clinker capacity of the kiln
- Economics are more viable if secondary fuel use can be increased in the kiln firing
- Investment cost are high for replacement of rotary or planetary cooler

3.5 Technology Paper No 5: Waste heat recovery

Waste heat from cement kilns is usually used for drying of raw materials like limestone, clay or marl. Depending on the humidity of the raw materials and the cooler technology, additional waste heat is available from the kiln gases (preheater exit gas) and cooler exhaust air. Principally, this heat can be used for drying of other materials like slag or secondary fuels or for steam or electric power production. As raw material drying is key for a cement plant, heat recovery has limited application for plants with higher raw material moisture content. Often, drying of other materials is recommendable and comparatively efficient as it is process integrated.

Steam or hot water production only makes sense if industrial consumers or district heating exist in the neighbourhood of the cement plant. Power production requires a heat recovery boiler and a turbine system. Power generation can be based on a steam process, the ORC (Organic Rankine Cycle) process or the KALINA process. The steam turbine is the technology best known from power plants. While in modern power plants the electric efficiency comes up to 45 – 46%, the relatively low temperature level of the waste heat in cement plants (200 – 400 °C) limits the efficiency to a maximum of 20 – 25%.

This technology has been developed and first implemented in Japan due to high energy costs and relatively low capital cost. From Japan the technology is now spreading to other plants, predominantly in China where it has become a kind of 'standard', as a way to respond to issues related to power supply to the industry as part of a national strategy. Relatively high power prices and low project costs have fostered this widespread of WHR initiatives in China. However, in many other regions with unstable power supply conventional autogeneration solutions are still preferred against WHR. Some interest is being detected in Europe, but high project costs are the main barrier.

The electrical efficiency of these installations is usually between 10 and 20%. The ORC and KALINA technologies use organic substances or NH_3 as cycling media which evaporate at lower temperatures and can therefore produce electric power at a temperature level at which steam turbines can't work efficiently. Nevertheless, the efficiency is normally less than 15%.

Based on the chosen process and kiln technology 8 to 10 kWh/t clinker can be produced from cooler waste air and 9 to 12 kWh/t clinker from the kiln gases if the moisture content in the raw material is low. So in total between 8 and 22 kWh/t clinker or up to 25% of the power consumption of a cement plant can be produced by using these technologies without changes of kiln operation. If higher power production is needed, WHR is in certain competition with energy efficiency of clinker production, but finally both techniques are aiming at a minimization of unused waste heat.. If kiln operation is modified in order to produce more electricity (higher preheater exit gas and cooler exhaust air temperature) up to 30 kWh/t clinker are possible Power generation can be further increased by additional co-firing into the boiler or by modification of the kiln system (e.g. less cyclone stages or bypassing upper stage(s)). Figures up to 45 kWh/t clinker have been reported. Depending on local conditions this can be an attractive option. Besides, under certain conditions it can make sense to use the residual energy content of the gases after WHR for cooling purposes.

Impact on energy consumption:

thermal: [MJ/t cli]

It is assumed that no additional fuel is used to produce more electricity than what is possible from waste heat and kiln operation has not been modified

electric: 8 to 22 [kWh/t cli]

Absolute power consumption of clinker production (increasing boiler and turbine) will slightly increase, but net power consumption will decrease

CO_2 reduction potential:

direct:

indirect: decrease 4 to 15 [kg CO_2/t cli]

The main influencing parameters are:

- No direct CO_2 emission reduction, indirect reduction depending on CO_2 intensity of external power production
- Installed power production
- Raw material humidity
- Cooler technology (no cooler exhaust air from satellite or rotary coolers)
- Heat already used for other purposes (e.g. drying of other materials)
- Power generation technology
- Waste heat available for heat recovery
- CO_2 intensity of the substituted power production
- If additional fuels are used: CO_2 intensity of fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli]
2015			15 to 25	0.3 to 1.2 decrease
2030			15 to 25	0.3 to 1.2 decrease
2050			15 to 25	0.3 to 1.2 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, a boiler/steam turbine cycle including construction, constant specific costs over time. Operating costs include power saving, personal and maintenance cost.
Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Availability of excess heat: raw material humidity is the key factor
- Investment cost are high for boiler, turbine and power generator
- Economics are ruled by power price/CO_2 price
- Clinker cooler technology: only grate coolers can provide waste air for heat recovery
- Efficiency is limited by a low temperature level
- Efficiency can be improved by using other media (organics, NH_3 …)
- Efficiency can be improved by using a combined gas and steam turbine or co-firing additional fuels
- Economics can be improved by firing secondary fuels
- minimum kiln capacity is needed
- Cost of additional manpower

3.6 Technology Paper No 6: Additional preheater cyclone stage(s)

The preheater cyclone is designed for heat transfer between hot gases from burning process and kiln feed. Energy savings can be achieved within certain limits to raw materials moisture by reducing the temperature of the hot gas through heat recovery with an additional cyclone stage.

Usually, the cement raw materials are dried in the raw mill with kiln exhaust gases. Therefore, the preheater of a cement kiln is designed based on the heat demand of the raw mill. This determines the number of cyclone stages of a new kiln. The raw material moisture depends on raw material type, geographical location and season. Worldwide it can vary in a range of minimum 2 -3 wt. % and in certain cases exceeding 20 wt.%. The temperature and therefore the enthalpy in the raw gas is strongly depending on the number of preheater cyclone stages. A 6-stage preheater precalciner plant using fossil fuels shows raw gas temperatures of about 280 °C, a 5-stage preheater 310 °C, a 4-stage preheater 350 °C and a 3-stage preheater (which is not very common) more than 500 °C. The higher the number of existing cyclone stages is the lower is the remaining reduction potential per cyclone stage.

The addition of a cyclone stage is only feasable, e.g. if the original design was very conservative, meaning that the raw material moisture content is below reference in relation to the given number of cyclone stages on-site. Another case is when high amounts of secondary fuels are used, especially in the calciner, and thus the preheater exit gas temperature has increased over time (sometimes by up to 50 °C).

The addition of a cyclone stage is a major retrofit because normally the preheater tower construction has been designed for the original number of stages. Often, the statics of the tower do not allow for an increase in height, and therefore structural load. As the upper cyclone stage is normally designed double string (for better dust separation) at least 2 stages have to be renewed. Furthermore, the additional cyclone stage creates an additional pressure drop, which can make a bigger exhaust gas fan necessary and which increases the electric power consumption of the kiln. This effect can be limited by using modern low pressure drop cyclones. Finally, dust cycling in the preheater can be affected (with effect on power consumption and kiln operation).

The energy demand of a 4-stage cyclone preheater kiln would e.g. decrease by 80 - 90 MJ/t clinker if a 5th stage is added with respect to reduced heat losses.

<u>Impact on energy consumption:</u>

thermal: decrease of 80 – 100 [MJ/t cli] (4 to 5 or 5 to 6 stage preheater, no add. power consumption)	electric: see below [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: 6 to 8 [kg CO_2/t cli]	indirect: see below [kg CO_2/t cli]

The main influencing parameters are:

- Raw material moisture content
- Site conditions (free space, material supply, statics of preheater tower)
- CO_2 intensity of the fuels
- Additional power demand if no low pressure drop cyclones are installed

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli]
2015			5 - 8	0.23 to 0.26 decrease
2030			5 - 8	0.23 to 0.26 decrease
2050			5 - 8	0.23 to 0.26 decrease

Remarks: The cost estimation covers 2 new cyclone stages (1 stage replaced, 1 additional stage, 2 string preheater) including construction and installation. A site specific cost estimation has also to include a new fan and/or preheater tower modification/rebuilding (etc.) as required. **Therefore, costs can increase significantly.** Against this background, additional electricity costs can be neglected, provided that low pressure drop cyclones are used.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Raw material moisture is the key factor
- Preheater tower construction might need to be adapted
- Heat required for drying of other materials must be taken into account
- Use of exhaust gas fans with adjustable speed drives may optimise the process
- Impact on efficiency is limited by already low temperature level of exhaust gas
- Technology is only applicable to dry preheater kilns
- Technology is in competition with waste heat recovery

3.7 Technology Paper No 7: Oxygen enrichment technology

In general, the use of oxygen enriched combustion air in the clinker burning process allows an increase of the energy efficiency, production capacity or substitution of fossil fuels by low calorific value or (secondary) fuels. That way the specific CO_2 emissions can be reduced. By the use of additional oxygen the nitrogen fraction of the combustion gas is decreased, which has to be heated up in the case of combustion with ambient air. Therefore the adiabatic flame temperature rises and the flame becomes shorter and brighter. The measure is limited by increasing damages of the kiln refractory and higher NO_X emissions due to increasing thermal NO_X formation in the sintering zone. In practice the application of the oxygen enrichment is still at an early stage, meaning that the technology contains potential for further optimization with respect to NO_x-emission reduction. Due to reduced secondary air flow the heat recuperation in the clinker cooler might be affected for example with a higher secondary air temperature as well.The oxygen enrichment technology is established in some cement plants in order to improve production capacity. An increase of 25 % to 50 % (short term experiments) kiln capacity by an oxygen enrichment to 30 - 35 vol. % in the combustion air has been reported. Other experiences show that under certain conditions oxygen enrichment is limited to an oxygen concentration of 23 to 25% in the combustion air. Oxygen enrichment has not been applied to reduce CO_2 emissions so far. But the use of enriched combustion air may result in fuel savings and thereby avoids CO_2 production. The decision for a dedicated oxygen supply system (on-site/off-site) depends on the specific need of the cement plant. Oxygen production itself leads to comparatively high additional power consumption.

Impact on energy efficiency:

thermal: decrease 100 to 200 [MJ/t cli]   electric: increase 10 to 35 [kWh/t cli]

CO_2 reduction potential:

direct: decrease 10 to 20 [kg CO_2/t cli]   indirect: increase 15 to 25 [kg CO_2/t cli]

The main influencing parameters are:

- Energy consumption of the air separation unit
- Clinker quality
- Type of oxygen supply
- Position of oxygen injection
- Oxygen purity (influences energy demand of oxygen production)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	5 to10	0.5 to 2.3 increase (compared to conventional firing)	5 to10	0.5 to 2.3 increase
2030	5 to10	0.5 to 2.3 increase (compared to conventional firing)	5 to10	0.5 to 2.3 increase
2050	5 to10	0.5 to 2.3 increase (compared to conventional firing)	5 to10	0.5 to 2.3 increase

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time. The calculation of the capital costs are based on a cryogenic air separation unit. The operational costs are additional costs to the base case and include additional power costs and fuel saving. An increased kiln capacity or increased secondary fuel consumption have not been taken into account as there exist separate technology papers for these topics. Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Integration of energy flows between the additional air separation unit and the cement plant
- Further development of oxygen supply technology has influence on process and financial conditions
- Durability of refractory lining and wear elements
- Economics are ruled by power price and investment costs

3.8 Technology Paper No 8: Upgrade plant automation/control package

The cement clinker burning process is a counter current process, meaning that the kiln is located in the middle of 2 heat exchangers which recover the heat of the combustion gases and the hot clinker. It has been shown by theory and proven by practice that such a system is principally a swinging system. Therefore optimum control of the kiln system is key for a smooth and energy saving process. Non-automated or non-optimum process control systems may lead to heat losses and moreover to unstable process conditions up to more operational stops. The latter effects lead to an increased fuel demand of the kiln for reheating the sintering zone. Automated computerised control systems are considerable measures to optimise combustion process and conditions. Today, all modern kilns are equipped with such systems.

Both, raw materials and fuel mix can be improved through analysis of chemical and physical characteristics. Besides automating the weighing and blending processes, other parameters like air and mass flow and temperature distribution can be controlled in order to optimise the kiln operation. Additional process control systems include the use of online analysers that permit operators to determine the chemical composition of raw materials and the product, thereby allowing for immediate changes in the blend of these materials. Process control of the kiln system can improve heat recovery, material throughput and a reliable control of free lime content in the clinker.

Energy savings relating to control systems compared to a kiln without such system may vary typically between 50 and 200 MJ per ton clinker. Often, a payback period of 2 years is typical for kiln control systems. Furthermore, an increased refractory life time under process controlled kiln operation has been reported. On the other hand, the reduction potential strongly depends on the technical equipment, the status of the plant, the availability of the plant and qualification of operating staff.

<u>Impact on energy consumption:</u>

thermal: decrease 50 to 200 [MJ/t cli]   electric: decrease 0 to 1 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: decrease 4 to 18 [kg CO_2/t cli]   indirect:decrease 0 to 0.7 [kg CO_2/t cli]

<u>The main influencing parameters are:</u>

- Initial status of the plant
- Instrumentation
- Education of staff
- CO_2 intensity of fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	0.25 to 0.35	0.22 to 0.63 decrease	0.25 to 0.35	0.27 to 0.74 decrease
2030	0.25 to 0.35	0.22 to 0.63 decrease	0.25 to 0.35	0.27 to 0.74 decrease
2050	0.25 to 0.35	0.22 to 0.63 decrease	0.25 to 0.35	0.27 to 0.74 decrease

Remarks: Investment costs may vary significantly due to plant configuration and level of instrumentation and automation.

The cost estimation is based on a clinker capacity of 2 mio. t/a (6,000 tons per day), constant specific costs over time.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, challenges:

- Existing Plant constellation predetermines further needs of equipment
- Educational level of operators and staff is of importance for process controlling
- Expert control systems simulate the best operator by using information from various stages in the process
- Computational modelled predictions may be used for future applications
- Electrically driven control fittings consume power

3.9 Technology Paper No 9: Alternative decarbonated raw materials for clinker production

The utilisation of alternative calcium containing raw materials which are already decarbonated offers a chance to reduce CO_2 emissions. This is a twofold chance since process-related CO_2 emissions from the decarbonation of the raw materials as well as CO_2 emissions from the related fuel consumption can be reduced. Blastfurnace slag, lignite ash, coal ash, concrete crusher sand, aerated concrete meal, corresponding fractions from demolishing wastes or lime residues from sugar industry are examples for such decarbonated alternative raw materials. The utilisation of alternative materials is in general limited by their overall composition since they need to be combined with the locally available raw materials to 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 VOC or trace elements and a variable composition may cause a further restriction in some cases. Furthermore the availability of such decarbonated raw materials is limited. 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. The following ranges are determined on the one side by the fact that the local situation may allow no or only a very limited use of alternative decarbonated raw materials. On the other side the use of granulated blastfurnace slag (GBFS) may be realistic up to 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.

Impact on energy efficiency:

thermal: decrease 100 to 400 [MJ/t cli]

electric: increase 0 to 2 [kWh/t cli]

(for a 15% replacement of raw materials by GBFS)

CO_2 reduction potential:

direct: decrease 0 to 117 [kg CO_2/t cli]

indirect: increase 0 to 2 [kg CO_2/t cli]

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

The main influencing parameters are:

- Composition of available raw materials at the considered plants
- Calcium content and content of other main elements of the alternative decarbonated materials which may limit their utilisation
- Decarbonated portion of calcium content
- Possibilities to improve the material by further treatment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	0 to 6	0 to 4.20 increase	0 to 6	0 to 4.20 increase
2030	0 to 6	0 to 4.20 increase	0 to 6	0 to 4.20 increase
2050	0 to 6	0 to 4.20 increase	0 to 6	0 to 4.20 increase

Remarks: Investment costs include the costs for storage and handling of the additional raw material: Operational costs include the costs for the alternative raw material, fuel saving, saving of replaced raw materials and additional power. In certain cases operational cost can be even negative, especially if waste materials are used and the cement company is paid for using them. Additional costs may occur by the impact on the raw meal wear which have not been taken into account in the cost estimation.

Conditions, barriers, constraints:

- The potential of the utilisation is generally determined by the raw materials on site and will therefore vary significantly at different sites
- Local availability of alternative materials may be quite different from site to site; some of these materials are generated all in all only at very few sites, additionally the use of such materials is in general limited close to their source
- The amount of alternative materials is in principle limited and different ways of utilisation may restrict the available amount additionally or may make it more expensive; granulated blastfurnace slag is, e.g., important as constituent of cement also in terms of reduction of CO_2 emissions, but it cannot be used twice; on the other hand the particular quality of such materials or particular local market conditions may leave room for the utilisation as raw material as well
- Availability may change due to changes in the supplying industry
- Efficiency is determined by decarbonated fraction which may vary strongly even for the same material, e.g., in case of concrete crusher sand
- Further treatment steps may improve the utilisation but need to be checked in terms of costs and environmental impacts

3.10 Technology Paper No10: Alternative fuels, replacing conventional fossil fuels

Based on the GNR data for the year 2006, the use of alternative fuels of the fuel energy demand of the cement industry on a global level was 7% and almost 3% was covered by biomass. The remaining 90% was provided by fossil fuels, mainly coal and petcoke. The variations on a global level in the different regions were significant: the 10% best of class (90% percentile) relating to all kilns came up to 23% alternative fuels and 10% biomass. From a technical point of view, much higher substitution rates are possible. This can be demonstrated from experiences in some European countries, where the average substitution rate reaches more than 50% for an industry sector and up to 80% as yearly average for single cement plants. Biomass share in pretreated industrial or domestic wastes can come up to 30 or 50%. As the fuel-related CO_2 emissions are about one third of the total emissions (325 of 866 kg CO_2 per tonne of clinker for the reference plant), the CO_2 reduction potential is significant if pure biomass is used. Summarized, the reduction potential strongly depends on the alternative fuel properties, the installed technology as well as other site specific conditions.

The CO_2 reduction potential of alternative fuels is principally based on two direct effects: first, many alternative fuels contain certain biomass content of which the CO_2 emission is accounted as zero. Second, most fossil alternative fuels have lower CO_2 emission factors related to the calorific value than coal or pet coke. Above that, there can be an indirect effect of emissions reduced outside the cement plant if wastes are used there instead of landfilling or incinerating them in separate installations. Pure biomass waste fuels used in the cement industry today are mainly animal meal, waste wood, sawdust and sewage sludge. Besides these fuels, many other organic waste materials are used as fuels in the cement industry on a lower level. Wastes containing biomass are mainly pre-treated industrial and domestic wastes (containing certain parts of organic fibres and textiles, paper, etc.).

Principally, in cement kilns conventional fossil fuels can be substituted up to 100% by alternative fuels. Nevertheless, there are certain technical limitations like the calorific value, the moisture content, and the content of side products like trace elements or chlorine. The calorific value of most organic material is comparatively low (10 – 18 GJ/t). For the main firing of the cement kiln an average calorific value of at least 20-22 GJ/t is required, meaning that high calorific alternative fuels are mostly used in the main firing. In the precalciner of modern cement kilns, in which up to 60% of the total fuel input is realised, the lower process temperature allows also the use of low calorific fuels. Therefore, precalciner kilns are able to utilize at least 60% of low calorific fuels.

A lower calorific value as well as high-chlorine content (requiring a chlorine by-pass system) will increase the specific fuel energy consumption per tonne of clinker. Therefore it is possible that although the use of alternative fuels can lead to lower energy efficiency, CO_2 emissions are reduced nevertheless. Furthermore, the use of waste fuels at higher substitution rates may limit or reduce clinker capacity. As the operation of cement kilns running at very high substitution rates (50-80%) differs significantly from the operation with conventional fossil fuels only, also penetration of technical operational experiences within companies or between different groups are also a major criterion for the use of such fuels on a global level.

Impact on energy consumption:

thermal: increase 0 to 300 [MJ/t cli] electric: increase 0 to 3 [kWh/t cli]

CO_2 reduction potential:

direct: decrease of 80 to increase of 200 [kg CO_2/t cli] indirect: increase 0 to 2 [kg CO_2/t cli]

The main influencing parameters are:

- For pure biomass wastes CO_2 emission will decrease
- Kiln type (technical equipment of the plant (silos, dosing station …)
- Fuel properties
- Biomass content of wastes
- Availability of biomass containing materials and/or biogenic material (competition with other industry sectors (power plants, steel industry)
- CO_2 intensity of fuel mix
- CO_2 intensity of (external) clinker production for the drying process of the biomass
- Maximum possible substitution rate of the fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli]
2015			5 to 15	2 to 8 decrease
2030			5 to 15	1 to 5 decrease
2050			5 to 15	0 to 2.5 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time, no inflation. Operational costs are expressed as savings and include only fuel cost savings as these are the main economic driver besides investment costs. Investment cost can vary significantly due to e.g. chemical composition and humidity of the secondary fuel(s). Many raw waste streams need rather expensive processing before they can be used as a kiln fuel. The corresponding costs (investment and operational) are not analyzed in this study, however, they are implicitly considered in the fuel cost assumptions. It is assumed that waste fuel prices will come up to about 30% of coal price in 2030 and 70% in 2050.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Availability, quality and price of waste fuels will be the key factor.
- Waste fuels may limit or reduce clinker capacity.
- Permitting conditions are important.
- Social acceptance of waste co-incineration is a problem in many countries.
- Lack of experience with waste fuel use in clinker burning process may occur in many regions.

3.11 Technology Paper No 11: Fuel switch (coal/petcoke →oil/gas/pure biomass)

In many industries fuel switch is one of the key measures for CO_2 reduction. Usually, the switch from coal to oil or gas is meant, but increasingly biomass is coming into focus. The CO_2 reduction potential of switching from hard coal (emission factor of ca. 95 kg CO_2/GJ) to heavy oil (78 kg CO_2/GJ) is about 18% whereas the switch to natural gas (56 kg CO_2/GJ) leads to a 40% reduction related to the energy content of the fuels. The emission factor of lignite (approximately 98 kg CO_2/GJ) is even higher. As in cement manufacture fuel related CO_2 emissions typically make up only one third of total emissions, the overall reduction potential of fuel switch is roughly one third of the percentages mentioned above. When comparing these options with other sectors, it has to be considered that the use of less carbon-intensive fuels does not allow the implementation of more energy efficient technologies nor does it allow significant reductions of investment in the case of new plants. In another sector like power generation, however, the use of liquid and gaseous fuels enables implementation of significantly more efficient technologies that also require less investment.

Based on the GNR data for the year 2006, 90% of the fuel energy demand of the cement industry on a global level was provided by fossil fuels, mainly coal and petcoke. The use of alternative fuels was 7% and almost 3% was covered by biomass. Gas and oil play a role in countries where these fuels are available at prices significantly below world market prices, particularly in oil and gas producing countries.. Technically, cement kilns can be operated with 100% oil or gas, but in many regions this is not economically viable under present conditions.

In most regions of the world, the main barrier for switching from coal and petcoke to oil and/or gas are higher costs. The price difference between these fuels is much more significant in the cement industry compared to e.g. the power sector because cement plants use mainly coal types with higher ash content and lower calorific values. The coal ash becomes part of the product and therefore brings an additional benefit to the operator. Beneath the fuel cost itself, a fuel switch could lead to additional disadvantages or extra costs: The use of gas for example is linked to the existence of gas pipelines which are not available everywhere. In cement kilns the switch from coal to gas does not bring any efficiency gain like in the power sector. In contrary, it usually leads to a limitation or decrease of the kiln capacity.

As the fuel-related CO_2 emissions are about one third of the total emissions, the CO_2 reduction potential is significant if pure biomass fuels are used. Pure biomass fuels used in the cement industry today are mainly biomass wastes like animal meal, waste wood, sawdust and sewage sludge. Principally, it is also possible to use energy crops as fuels, like natural wood or certain grass types (e.g. miscanthus), or other quickly-growing species. These materials have to be cropped, especially for the later use as fuels. Today this is not relevant for the cement industry globally for economic reasons.

CO_2 legislation will have a significant impact on the available quantities of biomass fuels which are available for the cement industry. Biomass costs will increase and will probably allow the separate planting of so-called cash crops to be burnt in any industry sector. If, like in Europe, power production from biogenic materials is subsidised by legislation, it will be even more difficult for the cement industry to receive significant quantities of these materials at acceptable costs.

Impact on energy consumption:

thermal: decrease of 200 to increase of 300 [MJ/t cli]

electric: increase 0 to 3 [kWh/t cli]

CO_2 reduction potential:

direct: decrease 50 to 20 [kg CO_2/t cli]

indirect: increase 0 to 2 [kg CO_2/t cli]

The main influencing parameters are:

- Availability of biomass fuels
- Fuel costs
- Fuel type (C / H ratio, calorific value)
- CO_2 intensity of fuel mix
- CO_2 intensity of (external) clinker production for the drying process of the biomass
- Maximum possible substitution rate of the fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli or cem]
2015			5 to 15	8 to 16 increase
2030			5 to 15	8 to 16 increase
2050			5 to 15	8 to 16 increase

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time, no inflation. Operational cost is expressed as additional costs and include only fuel costs as these are the main economic driver besides investment costs. Gas has not been considered due to too high prices. The development of biomass prices over time has not been predicted because it depends on many factors like energy and CO_2 policies, availability on regional level, etc.
Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Availability and price of biomass fuels will be the key factor.
- Biomass fuels may limit or reduce clinker capacity.
- Lack of experience with biomass fuel use in clinker burning process may occur in many regions.

3.12 Technology Paper No 12: Increase of the kiln capacity

As the clinker specific energy requirement is directly dependent on the dimension of the cement plant, an increase of the kiln capacity is linked with a reduction of specific CO_2 emissions. For higher clinker throughputs the plant components are larger dimensioned and consequently the total heat losses are increased. However relating to the produced amount of clinker (specific) heat losses fall with increasing plant size. That way the thermal energy consumption can be reduced. Due to decreased volume flows as a consequence of lower specific heat losses, it is also possible to reduce the electric energy demand (e.g. for fans). Investment in capacity increase can be an economically viable solution in growing markets or if 2 (or more) old kilns can be replaced by one new big kiln. The investment usually cannot be justified by the reduction of energy use or CO_2 emission only. In the first case, the main driver is the market need for more cement. In the second case, additional drivers are reduced maintenance and labour costs.

Principally a simulation study showed, that compared to a medium size plant with a clinker throughput of 3,000 t/d the thermal energy requirement rises by more than 200 MJ/t clinker for a 1,500 t/d plant, but is reduced by about 100 MJ/t clinker for a 5,000 t/d plant. Furthermore a new installation has the advantage of including other technologies for CO_2 emission reduction, e. g. a burner adapted for firing alternative fuels or waste heat recovery systems. Besides the reduction of specific heat losses the energy efficiency could be further increased by using advanced technology compared to older less efficient plants. That way it is possible to reduce the thermal energy efficiency by more than 400 MJ/t clinker by replacing two less efficient 3,000 t/d plants by one 6,000 t/d BAT-plant. As other technologies are described in other technology papers, this study only considers the described effect of capacity increase.

Although the energy efficiency is enhanced by increased kiln capacity, the replacement of smaller existing plants by one lager plant is linked with very high investment costs. Furthermore higher transporting distances for products as well as for raw materials and fuels can occur, leading to higher CO_2 emissions from transport. The level of capacity increase can be limited by the local availability of limestone (size of deposit).

<u>Impact on energy consumption:</u>

thermal: decrease 150 to 200 [MJ/t cli] electric: decrease 2 to 4 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: decrease 15 to 20 [kg CO_2/t cli] indirect: decrease 1 to 3 [kg CO_2/t cli]

The main influencing parameters are:

- Used technology for new installation (state of the art)
- Plant efficiency
- Local conditions (limited limestone deposit, raw meal and clinker properties etc.)
- Portion of alternative fuels
- Average transport distances for resources and products (additional fuel)

Remark: The impact on the energy consumption is relating to a comparison of a 3,000 t/d with a 6,000 t/d BAT- cement plant

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	240	1.4 to 1.7 decrease	-	-
2030	240	1.4 to 1.7 decrease	-	-
2050	240	1.4 to 1.7 decrease	-	-

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a (6,000 tons per day), constant specific costs over time. The operational costs are difference costs to the base case. They include power and fuel saving, labour and maintenance. Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- High investment costs
- Investment costs cannot economically be justified only by CO_2 reduction.

3.13 Technology Paper No 13: Retrofit mono-channel burner to modern multi-channel burner

State of the art burners in the cement industry are multi-channel burners which allow the use of different kinds of fuels at comparatively low primary air ratios. The primary air ratio describes the ratio of cold burner air and total combustion air. As primary air the whole air which is lead through the burner is understood (e.g. transport, swirl, axial air, etc.). Secondary and tertiary combustion air are preheated in the clinker cooler to 600 – 1000 °C (depending on cooler type and operation) and led to the kiln and the calciner respectively. If the primary ratio is reduced by replacing e.g. a mono-channel burner by a multi-channel burner a bigger share of hot combustion air can be taken from the cooler leading to a decrease of fuel energy demand.

In some regions of the world, mono-channel burners are also still in operation. Mono-channel burners are basically a refractory-lined single pipe with a nozzle. Primary air and fuel are conveyed together through the mono-channel for combustion into the rotary kiln. A mono-channel burner also has some operational disadvantages: the exit speed obtains a fixed velocity at the tip of the burner by design of the nozzle diameter. The velocity cannot be adjusted during operation. Furthermore, the shaping of the flame by changing the burner adjustment is also not possible during operation, e.g. in order to optimise the temperature profile in the sintering zone.

In many countries the mono-channel burner was replaced first by multi-channel burners (first generation). In the 1990s the so-called Low-NO_x burners were developed, which are based on a very low primary air ratio. In those countries where significant quantities of waste fuels are used, these Low-NO_x burners are being increasingly replaced by new multi-channel burners, again using higher primary air ratios.

If mono-channel burners are replaced by modern multi-channel burners, fuel energy can be saved because the latter require a significantly lower primary (burner) air volume flow. Therefore the efficiency of the clinker cooler, in which the combustion air is pre-heated, is increased. While mono-channel burners need primary air ratios of 20-25% (often the burners are in direct compound operation with the coal mill), modern multi-channel burners are operated with around 10-12%. Depending on the secondary air temperature, reduction of the primary air ratio by 5-10% will lead to a fuel energy saving of 50-80 MJ per ton clinker at conventional kilns and about half of this at precalciner kilns. The electrical energy demand will remain more or less unchanged as the higher consumption for control fittings and air delivery channels can be offset by the reduction of the primary air.

Besides the energy saving effect, modern multi-channel burners have several advantages concerning kiln operation: NO_x emission may be reduced due to the decreased oxygen availability in the core flame. Furthermore, these modern burners allow the use of significant amounts of secondary fuels. These effects are not considered further in this paper.

Impact on energy consumption:

thermal: decrease 25 to 75 [MJ/t cli] for a precalciner kiln

electric: no significant impact [kWh/t cli]

CO_2 reduction potential:

direct: 2.5 to 7 [kg CO_2/t cli]

indirect: no change [kg CO_2/t cli]

The main influencing parameters are:

- Reduction of primary air ratio
- CO_2 intensity of fuel mix
- Recuperation efficiency of clinker cooler

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli]
2015			0.4 to 0.5	0.08 to 0.25 decrease
2030			0.4 to 0.5	0.08 to 0.25 decrease
2050			0.4 to 0.5	0.08 to 0.25 decrease

Remarks: Investment cost based only on price for new burner and the reference precalciner kiln. Costs can be lower if only the difference between the new and the replaced cooler is taken into account. Saving can be doubled for a kiln without precalciner. Operational costs include absolute fuel cost only.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, challenges:

- Investment cost
- Trend of prices for primary and secondary fuels will determine this measure

3.14 Technology Paper No 14: Fluidized bed advanced cement kiln system

The rotary kiln is by far the predominant technology for cement clinker manufacturing world-wide. Besides, also a huge number of shaft kilns is still in operation, e.g. in China or India. Since the late 1990´s a Japanese company is developing a completely new kiln type based on fluidized bed technology (FBT). Also in Germany this technology has been developed for pre-calcining of cement raw materials and for clinker burning in the ´70´s, but today, no installation is in operation.

In the Japanese FBT kiln, clinker is produced in a fluidized bed system, under addition of grinded coal, and raw material injection. The raw material is granulated in the kiln system to a specific size. Subsequently the clinker is cooled in two steps (fluidized bed quenching and a packed bed cooler). The result is a finely granulated clinker.

In 1989 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 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. Therefore no information about investment costs is given.

Impact on energy consumption:

thermal: decrease up to 300 [MJ/t cli] electric: increase 9 kWh/t cli

CO_2 reduction potential:

direct: decrease up to 27 [kg CO_2/t cli] indirect: increase 4 to 6 [kg CO_2/t cli]

The main influencing parameters are:

- Technology not available for industrial application
- Clinker capacity
- CO_2 intensity of fuels
- CO_2 intensity of power generation

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	not available	up to 0.3 decrease	not available	up to 0.3 decrease
2030	not available	up to 0.3 decrease	not available	up to 0.3 decrease
2050	not available	up to 0.3 decrease	not available	up to 0.3 decrease

Remarks: The cost estimation is based on a clinker capacity of 1000 tons per day, constant specific costs over time. Operational costs only include fuel saving and additional power costs. Depreciation, interest and inflation are not included in operational costs.

Investment costs are not available

Conditions, barriers, constraints:

- Technology is not available for industrial application
- Larger possible capacity is not foreseeable
- Investment costs are not published

3.15 Technology Paper No 15: Cement grinding with vertical roller mills and roller presses

Nearly 40% of the electric energy used for cement production is spent on cement grinding. Ball mills still account for almost 60% of all mills in cement plants, followed by vertical roller mills and roller presses, each with 17%, and horizontal mills with 7%. A significant reduction of the specific energy demand for cement grinding can be achieved either by combined grinding in vertical roller mills (VRM) or high pressure grinding rolls (HPGR) in addition to the existing ball mills or by a complete replacement of ball mills. Theoretically the specific energy consumption related to ball mills amounts to 60 to 70% for both VRM and HPGR. Saving potentials are limited by the quality requirements of the final product and the specific system layout as well as auxiliary equipment installed. Whereas required grain sizes up to 4500 to 5500 Blaine in VRM and HPGR can be achieved, the resulting particle size distribution of the cement and thus cement performance can vary in the different systems raising the need for product quality control plans. The higher the pressure during comminution is, the narrower is the particle size distribution and the higher is the impact on water demand, strength development and setting time of the cement paste. Hence there is still need for further development of grinding technologies. In contrast combined grinding layouts being the most common systems installed, set the standard for product quality and do not have to face quality problems. These multi-stage configurations are, however, more complex to operate. Their saving potentials approach to 30% with an additional 80% increase in throughput as compared to single-stage grinding in ball mills. Despite that is has to be taken into account that the application of VRM and HPGR is connected to higher capital costs and requires additional maintenance efforts.

Impact on energy consumption:

thermal: - [MJ/t cli] electric: decrease 12 to 16 [kWh/t cem]

CO_2 reduction potential:

direct: - indirect: 7 to 11 [kg CO_2/t cem]

The main influencing parameters are:

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- Grinding technology
- Durability of wear and tear elements
- CO_2 intensity of the local electricity production equivalent to the retrenchment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	30	0.25 to 0.85 decrease	-	-
2030	-	0.25 to 0.85 decrease	-	-
2050	-	0.25 to 0.85 decrease	-	-

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time, no inflation; considered are the difference of costs for wear between ball mill and VRM/HPGR (0.15 to 0.75 €/t cem) and the energy savings.
Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Optimisation of cement qualities from single-stage grinding processes, which ensure required cement qualities (PSD □ RSSB slope < 1), has to be continued.
- Grinding efficiency could be improved by focusing on comminution by compression in future technologies.
- Efficiency of auxiliary units (e.g. disagglomerator, conveyor) needs to be taken into account when evaluating the entire grinding circuit.
- Durability is limited by wear of hard faced rolls and maintenance practices.

3.16 Technology Paper No 16: High efficiency separators

Open-circuit mills are not or only by high power demands able to achieve a product fineness of more than 3500 Blaine. Therefore they are connected to adjustable air separators and operated in a circuit. Separators divide the mill discharge into fines and coarse material, which is fed back into the mill again. A promising approach for the reduction of the specific energy demand of the cement grinding process is the application of high efficiency separators. Those are featuring optimized air ducts and additional extern air circuits. The high separation efficiency leads to higher proportion of classifier fines. As a result the number of circulations of the mill feed declines and the throughput rises by up to 15%. This also involves a reduction of the specific energy demand compared to grinding circuits with standard separators. High efficiency separators contribute to the energy demand for grinding with about 5 to 8%. Even if the energy demand is high, separators have a potential to contribute to an overall energy saving of 10 to 15%. The particle size distribution of the finished material will be slightly changed (lower proportion of fines), but not to the extent that the quality of the cement is significantly affected. To ensure process reliability and to use the separators to full capacity the operation parameters of the particular mill have to be adjusted, which is very often restricted by the still limited knowledge of the comminution mechanisms.

Impact on energy consumption:

thermal: - [MJ/t cli] electric: decrease 4 [kWh/t cem]

CO_2 reduction potential:

direct: - indirect: 2 to 3 [kg CO_2/t cem]

The main influencing parameters are:

- Clinker properties (grindability, moisture)
- Product quality (fineness, particle size distribution)
- CO_2 intensity of the local electricity production equivalent to the reduction

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	2.5	0.28 decrease	2.5	0.28 decrease
2030	2.5	0.28 decrease	2.5	0.28 decrease
2050	2.5	0.28 decrease	2.5	0.28 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time; considered are the increased maintenance effort and the savings in electrical energy.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Knowledge of comminution mechanisms is still limited.
- Measurement and control techniques have to be improved.
- The separator technology has to be optimised for each application.
- The impact of grinding aid has to be specified for each product (e.g. workability).

3.17 Technology Paper No 17: Optimization of operating parameters of ball mills

Nearly 60% of the electric energy used for cement production is spent on grinding processes. Ball mills still account for almost 60% of all mills in cement plants. An optimization of the huge number of established ball mills implies high savings potentials. The adaptation of operating parameters represents an attractive approach due to the fact that almost no additional capital costs are required. Parameters that hold potential energy savings are load level, revolution speed, combination of the ball charge, lining design and the adjustments of the separator. Standard optimization methods include meter sampling of the effective length as well as separator sampling. By determination of the particle size distribution electric energy reduction potentials can be revealed. In addition to that enhanced measures have been developed which allow a more directed control of the grinding process. This includes electric ears with a downstream frequency analysis for a wide range of oscillations or online monitoring systems for the discharge of the mill. Basing on this information expert control or fuzzy logic systems can support mill optimization. The main obstacles are the complex interdependences between the mentioned parameters. To reduce the specific power demand of ball mills while still assuring operation reliability the comprehension of the processes inside the grinding chamber has to be enhanced. The modelling and simulation of ball mills has proven to be effective methods for obtaining further understanding.

Impact on energy consumption:

thermal: - [MJ/t cli] electric: decrease 0 to 2 [kWh/t cem], depends on mill evaluation

CO_2 reduction potential:

direct: - indirect: 1 to 2 [kg CO_2/t cem]

The main influencing parameters are:

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- CO_2 intensity of the electricity generation mix in the region

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	-	-	0.01	0 to 0.15 decrease
2030	-	-	0.01	0 to 0.15 decrease
2050	-	-	0.01	0 to 0.15 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time; considered are the savings in electrical energy as well as reduced cost for wear.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints:

- Deeper understanding of the grinding process is necessary.
- Methods for modelling and simulation of the comminution have to be improved.
- Better measurement and control techniques are needed for a significant step of process improvement

3.18 Technology Paper No 18: Variable speed drives

Electrical drives are the main power consumer in the cement production process with widespread need for flow rate control. Motors and drives are used to drive fans, rotate the kiln, transport materials and, most importantly, for grinding. More than 500 up to 700 electric motors may be used, varying widely in their electrical capacity. Most motors are fixed speed AC models. In cement plants large variations in load occur. Hence, motor systems are often operated at partial load. Decreasing throttling can reduce energy losses in the system and coupling losses through the installation of variable speed drives. Dampers have least energy efficiency of the available controls that can be retrofitted. The most energy efficient one is the variable speed drive. Therefore, the control method employed has a major effect on the operating costs. The power consumption of rotational fans and pumps follows affinity rules. That means that the reduction to 80% of the rotational speed of a unit leads to energy savings by almost 50%. Frequency controlled equipment is used more and more in cement plants, but the application may vary widely, depending on electricity costs. Especially motors like drives of big fans (e.g. exhaust gas or air fans) are often equipped with variable speed drives.

Power use in the reference cement plant is 111 kWh per ton cement but can show significant variation in industrial practice. Variable speed drives with improved control strategies and high-efficiency motors can help to reduce power use in cement kilns. Presuming a low degree of implementation, power savings may vary considerably n a plant in a range from 3 to 9 kWh per ton cement.

Energy savings depend strongly on the application and flow pattern of the system on which the adjustable speed drive is installed. The electrical energy savings through frequency controlled drives may therefore vary in a wide range (in practise between 7 and 60%).

Additional benefits of variable speed drives are the process controllability via process control system, the availability and reduced motor noise as well as elimination of fan vibration. On the other hand, energy savings may be limited if the kiln is usually operated at it's maximum capacity.

Impact on energy consumption:

thermal: [MJ/t cli] electric: decrease 3 to 9 [kWh/t cem]

CO_2 reduction potential:

direct: [kg CO_2/t cli] indirect: 1 to 5 [kg CO_2/t cem]

The main influencing parameters are:

- Initial level of implemented drives in the specific plant
- Power requirement
- Application area
- Flow is proportional to rotational speed

- Power is proportional to cube of rotational speed
- CO_2 intensity of (external) power supply

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cem]
2015			0.25 to 0.35 (1.000 kW)	0.3 to 0.7 decrease
2030			0.25 to 0.35 (1.000 kW)	0.3 to 0.7 decrease
2050			0.25 to 0.35 (1.000 kW)	0.3 to 0.7 decrease

Remarks: The price is strongly depending on the power requirement of specific speed drive. Above mentioned investment cost relates to a complete medium voltage driven unit with transformer, frequency converter and one motor.

Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, challenges:

- Process control system with frequency controlled drives may stabilise process conditions
- Level of clinker production related to kiln capacity
- Economics are depending on CO_2 and power price

3.19 Technology Paper No 19: Separate grinding of raw material components

For preparation of the raw mix for cement clinker production it is typically necessary to add different corrective components to the mix. Normally the grindability of the diverse constituents in the raw mix is different. This results in higher specific energy demand for comminution of materials with worse grindability and a lower throughput of the combined grinding of all components. Therefore it can be efficient to grind the raw material components separately. If it is possible to operate these grindings on systems with different specific energy demand there can be a benefit if the components with a high proportion in the raw mix are ground on a system with a low specific energy demand.

The most common application of this would be separate grinding of sand or slag, which are both much harder to grind and more abrasive than traditional raw materials. Separate grinding of slag is desirable with a high usage rate and can benefit from using a vertical mill or a separate ball mill.

An additional benefit from separate grinding of raw material components could come from improved burnability of the raw meal in the kiln. Rather than the current compromise of combined grinding, where the softer components may be ground finer than necessary and the hard components (often sand) are not ground sufficiently fine, separate grinding would enable production of a raw meal with differentiated fineness of different components with different impacts of fineness on burnability. This would be a very site specific effect and hard to quantify generally.

<u>Impact on energy consumption:</u>

thermal: [MJ/t cli]

electric: decrease 1 to 1.4 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct:

indirect: 0.7 to 1 [kg CO_2/t cli]

<u>The main influencing parameters are:</u>

- Properties of raw material from quarry
- Grindability of raw mix components
- Grinding technology
- CO_2 intensity of the power production

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	35	0.90 increase	40	0.90 increase
2030	35	0.90 increase	40	0.90 increase
2050	35	0.90 increase	40	0.90 increase

Remarks:

- The cost estimation is based on a clinker capacity of 2 mio. t/a, constant specific costs over time. Replacement of an existing vertical roller mill by ball mill (40 t/h) and high pressure grinding rolls (360 t/h). If raw material grinding is processed with 2 existing ball mills, the investment can be much lower (about 10 Mio. EUR). Also for greenfield plants the investments will be less than 40 Mio. EUR if operation of 2 raw mills is planned from the beginning.
- Depreciation, interest and inflation are not included in operational costs.
- No additional personnel costs calculated.
- Operational costs include maintenance costs only for the additional grinding system and the difference of costs for electric energy between operation of vertical roller mill and high pressure grinding roll plus ball mill.

<u>Conditions, barriers, constraints:</u>

- High pressure grinding roll is not able to grind material with high moisture (max. ca. 6%); for high moisture in raw material is an additional dryer necessary.
- High investment costs compared to very limited effect if installation of a 2nd mill is necessary.
- The handling of separate ground sand (dry process) can be problematic (risk of silicosis). As a result, separate grinding of sand almost has to be by wet grinding in a ball mill. This can add additional costs and issues from drying of the sand slurry.

3.20 Technology Paper No 20: Advanced grinding technology

Grinding processes requires more than 60% of the electric energy demand for cement production. Energy utilisation at comminution with actual available technology is low. Therefore in principle the further development of grinding technologies holds huge saving potentials. State of the art grinding equipment still features mainly ball mills and with increasing tendency vertical roller mills, high pressure grinding rolls and to a low fraction horizontal roller mills. These types of mills apply focused comminution by compression which leads to a serious reduction of the specific energy demand compared to ball mills. The wear of rollers is higher than wear in ball mills. Whereas required grain sizes up to 4500 to 5500 Blaine in VRM and HPGR can be achieved, the resulting particle size distribution of the cement and thus cement performance can vary in the different systems raising the need for product quality control plans. The higher the pressure during comminution is, the narrower is the particle size distribution and the higher is the impact on water demand, strength development and setting time of the cement paste. Nevertheless the further development of comminution by compression constitutes the most promising approach towards new grinding technologies. To reduce wear and to ensure stable operation material and design of the rollers have to be optimized. In addition to that optimal comminution depends on the compression-force as well as the thickness of the grinding bed. Therefore new mill designs should allow the independent adjustment of the grinding force and the thickness of the grinding bed. A prototype which meets these concerns has already been developed. Modifications of classical 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 auspicious. Examples are the ultrasonic-comminution or the plasma comminution. In ultrasonic-comminution the energy needed for crushing is transferred to the material by acoustic pulses. The system has been tested for slag grinding in model scale only. Plasma comminution is performed in a liquid by using shock waves. The application is still limited to semiconductor materials. A complete different approach is followed by low temperature comminution. In this case the particle size reduction is achieved by a rapid reduction of the energy level. In summary it is perceptible that there is need for much further development of alternative grinding methods. Yet the definitive next generation grinding technology can not be outlined. In medium term the enhancement of (high pressure) comminution by compression constitutes the only promising approach. Above all detailed comprehension of the breakage processes of materials is required. Only on the basis of such fundamental research efforts an effective optimization or redesigning of existent grinding technology is possible. For the above reasons, it is currently not possible to provide concrete details on economy of future grinding technologies. Therefore a statement regarding energy efficiency, CO_2 and cost savings is still not possible.

Impact on energy consumption:

thermal: [MJ/t cli]   electric: no estimation possible

CO_2 reduction potential:

direct: -   indirect: no estimation possible [kg CO_2/t cem]

The main influencing parameters are:

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- Energy demand for breakage of material
- Physical limitations for energy transfer
- Material science and grinding technology
- Durability of wear and tear elements
- CO_2
- Intensity of the power production equivalent to the retrenchment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015	n/a	n/a	n/a	n/a
2030	n/a	n/a	n/a	n/a
2050	n/a	n/a	n/a	n/a

Remarks: General cost estimation not possible at the current stage of development.

Conditions, barriers, constraints:

- Fundamental research in material science required
- Enhancement of the understanding of breakage processes
- Enhancement of the understanding of abrasive wear
- Increase of durability of hard faced rolls
- Development of new hard facing materials
- Development of new grinding plant layouts
- Development of new principals for energy transfer for breakage

3.21 Technology Paper No 21: Further reduction of clinker content in cement by use of granulated blast furnace slag

Cements containing granulated blast furnace slag (GBFS) are very common in Europe. Their production involves the intergrinding of clinker with granulated blast furnace slag as another main constituent. As less clinker is needed per ton cement, CO_2 emissions from fuel combustion and from decarbonation of limestone can partially be saved.

The production of cements with GBFS as a main constituent requires additional electricity for blending and grinding and additional fuel for drying. However, the use of GBFS does not lead to a significant change in the electricity consumption since the additional utilisation is largely offset by the savings which result from the reduced production of clinker. The thermal energy consumption of the cement production decreases almost linearly with an increase in the GBFS proportion. The partly vastly different properties of the cement are disregarded in this approach due to reduced clinker production.

Many advantageous cement properties strongly depend on the clinker and are often reduced to the same extent as the reduction of the clinker/cement ratio. For example, short term strength of cements containing GBFS may be diminished significantly. On the other hand, the use of GBFS as main constituent of cement can lead to higher long term strength and improved resistance to acids and sulphates. Cements with higher amounts of GBFS are often suitable as LH cements, i.e. cements releasing low heat of hydration, e.g. for massive constructions. Furthermore, these cements offer a lower alkali-silica reactivity. This can allow a reduction in energy consumption needed to remove high alkali containing kiln dusts from the kiln bypass system.

As an example, the European standard EN 197-1 defines 9 cement types with up to 95% by mass GBFS and up to 80% by mass of a combination of GBFS and pozzolana (where the maximum amount of GBFS is 50% by mass). Several main constituents can be combined in Portland-composite cements. The technical performance and the application of cements with very high contents of other main constituents (even higher than the limit values defined in the standards) are investigated and discussed at present in many countries as well as e. g. on the European level. However, in practise the amount of GBFS in technically used cements ranges usually from 30 to 70% by mass, therefore these values will be used for the following estimations. Furthermore, they are based on the reference plant data as a starting point (see "key assumptions" in Annex). The calculations are based on the reference plant data. Therefore, the reduction potential is higher if OPC is replaced by slag containing cement

The availability of GBFS mainly depends on the pig iron production. Actually about 200 Mill. t/a GBFS are produced worldwide.

<u>Impact on energy consumption:</u>

thermal: decrease of 420 to 1,880 MJ/t cement electric: no significant influence

(for a cement with 30 to 70% by mass GBFS, additional fuel for slag drying, energy demand for slag granulation and for transport are not taken into account)

CO_2 reduction potential:

direct: reduction 100 to 430 kg CO_2/t cement
for a cement with 30 to 70% GBFS
(assumed that GBFS is accounted "CO_2-free" for the cement production)

indirect: no reduction

The main influencing parameters are:

- Availability (depends mainly on steel production, level of slag granulation, use of GBFS in products other than cement)
- Quality and price (incl. logistics) of GBFS
- Amount of GBFS in cement
- CO_2 intensity of clinker production

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015			5 to 10	
2030			5 to 10	
2050			5 to 10	

Remarks:

- Capital costs are due to extra storage capacity for GBFS (if necessary) and the new cements as well as the technical equipment for handling and drying of GBFS
- It is assumed that one extra cement silo will be needed, but no silo for the GBFS which can be stored outside
- Furthermore, investment costs include technical equipment for handling and drying of the GBFS
- Operational cost savings depend on the purchase costs of GBFS, reduced fuel costs for clinker production, reduced electricity costs for kiln drives and bypass, increased electricity costs for raw material and cement grinding, increased fuel costs for drying of GBFS, reduced handling and mining costs, common or separate grinding of slag.
- These costs need to be assessed on the basis of individual plants and cement types

Conditions, barriers, constraints:

- Availability (depends mainly on level of raw iron production, level of slag granulation, and competitive situation concerning GBFS use e. g. as decarbonated raw material for clinker production or as basic material for future production of geopolymers)
- Quality (in particular homogeneity)

- Prices of GBFS
- Logistics
- Technical performance of concrete produced with cements containing GBFS (e.g. strength development, durability)
- Standards and regulations
- Market acceptance

3.22 Technology Paper No 22: High performance cements resulting in reduction of the cement content in concrete

A theoretical possibility for the reduction of CO_2 in concrete buildings, which is often mentioned or discussed, is the use of high performance cements in place of conventional cements. The use of cements of a high strength class (52.5) in place of a cement of a lower strength class (32.5) is conceivable. 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 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.

High performance concretes also do not contain reduced, but on the contrary even increased cement contents. Such concretes are favourable for example if they lead to a decrease of the required amount of concrete in slim construction units. Related to the functional unit of the concrete construction member, a potential CO_2 reduction can in fact result.

The use of high performance cements 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.

Nevertheless, in newly industrialising countries with less modern concrete technology concrete might be produced with higher proportions of cement than technologically necessary. However, this topic is beyond the scope of this paper.

Impact on energy efficiency:

thermal: no significant impact expected electric: no significant impact expected

CO_2 reduction potential:

No relevant CO_2 reduction potential during cement manufacturing expected

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015				
2030				
2050				

Conditions, barriers, constraints:

- Workability and the durability of the concrete
- Danger of corrosion of reinforcing steel
- Minimum cement contents defined in the rules and standards for concrete

3.23 Technology Paper No 23: Impact of very high/very low lime saturation factor

The lime saturation factor (LSF) of Ordinary Portland Cement (OPC) clinker typically ranges between 90 and 102. Usual OPCs have LSFs of up to 97. Higher LSFs are generally aspired for fast setting OPCs with high early strengths. A change of the LSF of 1 is combined with a change the absolute CaO content of the clinker in an order of around 0.2 to 0.4% by mass.

The production of OPC with very high LSFs of more than 100 leads to increased CO_2-emissions due to the calcination of higher amounts of $CaCO_3$ in the raw meal as well as higher burning temperatures required for such raw meals. A decreased energy consumption in the grinding process is not to be expected since the high temperatures also lead to denser microstructures of the clinker granules with consequentially worse grindabilities. Additionally, higher amounts of valuable pure limestone are required to achieve higher LSFs. Finally, LSFs higher than 102 will lead to high amounts of free lime, which does not contribute to the strength development of the cement, but may affect its soundness.

OPCs with lower LSFs are produced with a lower limestone content in the raw meal, thereby reducing the CO_2 emissions resulting from calcination. Furthermore, raw meals with lower LSFs require lower burning temperatures due to better burnability. This reduces the energy consumption of the burning process. Relating to local conditions kiln capacity can be slightly increased. Additionally, lower LSFs can reduce the required amounts of valuable pure limestone in the raw meal, what depends on the particular local resources.

The main disadvantage of OPCs with low LSFs compared to OPCs with higher LSFs is the reduced content of alite and the consequential lower early strength at an equal fineness. To a limited degree the early strength of an OPC can be increased by a higher fineness of the cement. The amount of electric energy necessary for the additional grinding is hard to predict, since the change of grindability with decreasing LSF depends on the phase composition of the clinker as well as on its microstructure. Generally higher amounts of belite, which is harder to grind than alite, might decrease the grindability of the clinker. The less dense microstructure of a clinker burnt at relatively low temperatures might increase its grindability, but this effect is only relevant for relatively coarse cements, since the additional amount of energy required to gain a higher fineness rises with the fineness.

Impacts of lower LSFs and higher finenesses of clinker on the strength development of cements with more than one main constituent are unpredictable, since the interactions between clinker particles and other constituents always depend on both fineness and chemical composition of all reactants.

Impact on energy consumption:

thermal:	decrease of 100 MJ/t cli for an assumed decrease in LSF of 10 no production increase assumed	electric:	increase of 10 to 20 kWh/t cem for an assumed decrease in LSF of 10

CO$_2$ reduction potential:

direct: reduction of 40 kg CO_2/t cli (for an assumed decrease in LSF of 10)

indirect: increase of 5 to 14 kg CO_2/t cli

The main influencing parameters are:

- Decrease of the CO_2-releasing component ($CaCO_3$) in the raw meal
- Decrease of the fuel consumption due to lower burning temperatures
- Increase of the energy consumption for grinding to achieve a higher cement fineness
- Grindability of belite-rich clinker
- CO_2 intensity of fuel mix
- CO_2 intensity of (external) electricity consumption

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015				
2030				
2050				

Remarks:
- Special investments for new installations or for retrofits are not necessary
- The operational costs depend on the particular local resource situation, the actual grindability of the clinker and the combination of LSF-reduction and fineness increase, which will have to be estimated for individual plants

Conditions, barriers, constraints:

- Technical performance of concrete produced with cements with lower LSF (in particular strength development, water demand)
- Regulation of strength by means of fineness is limited
- Impact on cements with more than one main constituent has to be investigated
- Market acceptance

3.24 Technology Paper No 24: Further reduction of clinker content in cement by use of fly ash

Several main constituents besides clinker are available for the production of blended cements. The production of cements containing fly ashes leads to a reduced clinker content of cement, thus CO_2 emissions from fuel combustion and from decarbonation of limestone during clinker production can partially be saved.

Fly ash is obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases of furnaces fired with pulverised coal. Fly ash may be siliceous or calcareous in nature. The former is a fine powder of mostly spherical particles having pozzolanic properties; the latter may have, in addition, hydraulic properties. Siliceous fly ash consists essentially of reactive silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3), calcareous fly ash of reactive calcium oxide (CaO), reactive silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3). There are several requirements concerning the constitution of the used ashes. For example, the reactive silicon dioxide content of siliceous ashes shall not be less than 25% by mass and the proportion of reactive calcium oxide of calcareous ashes shall not be less than 10% by mass. The latter may have critical sulfate (SO_3) and/or free lime contents. The sulfate content has to be taken into account for the manufacture of cement by appropriately reducing the addition of calcium sulphate containing constituents in cement manufacture. Furthermore, many fly ashes contain higher amounts of unburned carbon affecting their suitability for cement or concrete. In these cases, the level of unburned carbon can be diminished by various techniques.

Fly ash often requires additional electricity for blending. Grinding is mostly not necessary; therefore fly ash can be added e.g. directly into the classifier. This leads to a decrease of electricity consumption for the cement grinding process. The thermal energy consumption of the cement production decreases almost linearly with an increase in the fly ash proportion. The partly vastly different properties of the cement are disregarded in this approach.

The use of siliceous fly ash as a cement constituent can lead to a decrease of the water demand, an improved workability, a higher long term strength and a higher density of the microstructure of the components. Beside this the durability, e.g. the sulfate resistance of the concrete made with fly ash containing cement will be increased. Furthermore, these cements offer a lower alkali-silica reactivity. This can allow a reduction in energy consumption needed to remove high alkali containing kiln dusts from the kiln bypass system.

However, the advantageous cement properties strongly depend on the clinker properties and are often reduced to the same extent as the reduction of the clinker/cement ratio. For example, short term strength of cements with fly ash as a main constituent may be diminished significantly. The use of fly ashes requires additional electricity for blending and grinding, if a pretreatment of the used ash is necessary.

According to the European standard EN 197-1, the production of various cement types containing siliceous and calcareous fly ash is possible. These cement types are CEM II/A-V and -W, CEM II/B-V and -W, CEM II/A-M, CEM II/B-M, CEM IV and CEM V (siliceous fly ash only) with fly ash contents from 6% to 55% by mass. The rate of fly ash containing cements in cement production differs from one to another country. While cements with siliceous fly ash are common e.g. in France, this technology is in its infancy in other countries like Germany. Due to the high variability of its composition and the possibly high amount of sulfate the production of cements containing calcareous fly ashes is not very common in Europe until today. In practise the proportion of fly ash in technically used cements is usually limited to a value of around 25 to 35% by mass, therefore these values will be used for the following estimations.

The possibility to use fly ash as a constituent of cement depends strongly on the availability of the fly ash. With respect to the CO_2 discussion the future number and capacity of coal fired power plants is hardly to predict. Actually, about 500 Mill. t/a fly ash are produced worldwide, about 120 Mill. t/a are used in the cement and concrete industry. The provision for additional saving potentials based on fly ash decarbonation techniques is beyond the scope of this paper, but is covered in the state of the art-paper No 4.

The calculations below are based on the reference plant data as a starting point (see "key assumptions" in Annex). Therefore, the reduction potential is higher if OPC is replaced by fly ash containing cement.

<u>Impact on energy consumption:</u>

thermal: decrease of 220 to 600 MJ/t cement (for a cement with 25 to 35% by mass fly ash)

electric: decrease of 15 to 27 kWh/t cem

<u>CO_2 reduction potential:</u>

direct: reduction of 50 to 140 [kg CO_2/t cem] (for a cement with 25 to 35% by mass fly ash)

indirect: reduction of 8 to 19 [kg CO_2/t cem]

<u>The main influencing parameters are:</u>

- Type, availability, quality and price (incl. logistics) of the fly ashes
- Amount of fly ash in cement
- Durability of concrete produced with fly ash containing cements
- CO_2 intensity of clinker production

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015			8 to 12	
2030			8 to 12	
2050			8 to 12	

Remarks:

- Capital costs are due to extra storage capacity for the fly ashes and the cements as well as the technical equipment for handling (drying etc).
- Operational cost savings depend on the purchase costs of the fly ashes, reduced fuel costs for clinker production, reduced electricity costs for kiln drives and bypass, decreased electricity costs for cement grinding, reduced handling and mining costs.
- These costs need to be assessed on the basis of individual plants and cement types.

<u>Conditions, barriers, constraints:</u>

- Sources, availability, quality (in particular homogeneity) and prices of the fly ashes
- Logistics
- Technical performance of concrete produced with fly ash cements (e.g. workability, strength development, durability)
- Standards and regulations
- Market acceptance
- Further research is required concerning the reactivity of fly ashes in general and the use and handling of calcareous fly ash in cement

3.25 Technology Paper No 25: Further reduction of clinker content in cement by use of pozzolanas

Several main constituents beside clinker are available for the production of blended cements. The production of cements containing pozzolanic materials reduces the amount of clinker needed for the cement production. Thus CO_2 emissions from fuel combustion and from decarbonation of limestone during clinker production can partially be saved.

Pozzolanas are defined as substances of siliceous or silico-aluminous composition. Finely ground pozzolanic materials react in the presence of water at normal ambient temperature with dissolved calcium hydroxide ($Ca(OH)_2$) to form strength-developing calcium silicate and calcium aluminate compounds. In general, the use of a pozzolana as a main constituent of cement is possible if the content of reactive silicon dioxide amounts not less than 25% by mass. Often a differentiation is made between natural pozzolana and natural calcined pozzolana. Natural pozzolanas are usually materials of volcanic origin or sedimentary rocks with suitable chemical and mineralogical composition (e.g. pumice). Natural calcined pozzolanas are materials of volcanic origin, clays, shale or sedimentary rocks, activated by thermal treatment. Metakaolin is a well-known example for natural calcined pozzolana. Kaolin as raw material for metakaolin may also be produced from non-natural sources, e.g. oil sands tailing ponds.

The production of cements with pozzolanas as a main constituent involves the pre-treatment of the pozzolana like crushing, drying and grinding and the intergrinding or mixing of the cement clinker with the pozzolanic material. The electric energy consumption is assumed to be slightly lower because of better grindability of most pozzolanas compared to the replaced clinker. For the production of natural calcined pozzolanas further energy demand for the calcination of the pozzolana (e.g. clay) is required. The thermal energy consumption of the cement production decreases almost linearly with an increase in the pozzolana proportion if the pozzolana has not to be calcined. The partly vastly different properties of the cement are disregarded in this approach.

Cement properties diversify depending on the used pozzolanic materials, their chemical and mineralogical composition, their fineness and therefore their reactivity. Because the pozzolanic reaction does not start as fast as the clinker reacts, in general the early compressive strength of cement decreases with increasing the amount of e.g. pumice and an analogous decrease of the amount of clinker. On the other hand, the use of pozzolana as a main constituent can lead to better workability of the concrete due to a better grain size distribution as well as to higher long term strength and improved chemical resistance.

The use of natural pozzolanas as main constituent of cement is common e.g. in Europe. According to the European standard EN 197-1, the production of various cement types containing “natural pozzolana” and “natural calcined pozzolana” from 6 % to 55% by mass is possible. However, cements containing natural calcined pozzolanas are not produced in appreciable amounts until today, probably because of additional costs for the calcination step.

In practise the proportion of pozzolana in technically used cements is usually in a range of 15 to 35% by mass; therefore these values will be used for the following estimations. Furthermore, the calculations below are based on the reference plant data as a starting point (see “key assumptions” in Annex).

The availability of pozzolanas mainly depends on the local geological conditions. In 2003 about 30 Mill. t pozzolana were used worldwide, but only about 50% in cement and concrete industries. The increased use of pozzolanas for cement manufacturing will imply larger transport distances, which are not taken into account in this study.

Impact on energy consumption:

thermal: decrease of in the range of 0 to 600 MJ/t cement

electric: decrease of 0 to 25 KWh/t cem

CO_2 reduction potential:

direct: reduction in the range of 0 to 140 kg CO_2/t cement (for a cement with 15 to 35% by mass pozzolana, no additional fuel for pretreatment)

indirect: decrease of 0 to 18 kg CO_2/t cem

The main influencing parameters are:

- Type, availability, quality and price (incl. logistics) of the used pozzolana
- Amount of pozzolanas in cement
- Necessity of calcination of the pozzolanic material
- Durability of concrete produced with pozzolana containing cements
- Transport distances for pozzolanas

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015			8 to 12	
2030			8 to 12	
2050			8 to 12	

Remarks:

- Capital costs are due to extra storage capacity for the pozzolana and the cements as well as the technical equipment for handling and drying of the pozzolanas
- 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 pozzolanic materials, reduced fuel costs for clinker production, reduced electricity costs for kiln drives and bypass, decreased electricity costs for cement grinding, reduced handling and mining costs
- These costs need to be assessed on the basis of individual plants and cement types

Conditions, barriers, constraints:

- Sources, availability, quality (in particular homogeneity) and prices of the pozzolanas
- Logistics
- Technical performance of concrete produced with blended cements (e.g. workability, strength development, durability)
- Standards and regulations
- Market acceptance

3.26 Technology Paper No 26: Further reduction of clinker content in cement by use of other materials

The clinker content of cement can be reduced significantly by use of other main constituents like e.g. blast furnace slag, fly ash, pozzolanas or limestone. The use of these main constituents is regulated in different national standards. In many cases, several main constituents are combined in so-called composite cements. The technical performance and the application even of new cement types with very high contents of different main constituents are investigated and discussed at present. The use of blast furnace slag, fly ashes and pozzolanas as main constituent is described in other Technology Papers. Limestone and other materials that can be used as cement constituent are described here. A very simple and efficient method to reduce the clinker/cement ratio is the intergrinding of limestone as a minor or main constituent. Limestone is easy to grind and usually well available for cement plants.

The replacement of clinker with limestone reduces CO_2 emissions from fuel combustion and from decarbonation of limestone otherwise caused by clinker production. The impact on electricity demand relates strongly to the used material. E.g., the grindability of limestone is much better compared to the replaced clinker. On the other hand, the production of silica fume is more electricity consuming that clinker grinding. Limestone cements can lead to better workability of the concrete and a lower alkali-silica reactivity. This can allow a reduction in energy consumption needed to remove high alkali containing kiln dusts from the kiln bypass system. However, if limestone containing cements are adjusted to give the same strength like OPC they have to be ground more finely. The monocarbonate ($3CaO \cdot Al_2O_3 \cdot CaCO_3 \cdot 11\ H_2O$) which is formed by reaction of the limestone with the calcium aluminate during cement hydration does not contribute to strength formation. The resistance to acids and sulphates and the freeze-thaw-resistance of limestone containing cements may be impaired. Therefore the proportion of limestone in cements has usually been limited to around 25 to 35% by mass.

Binders especially used for masonry mortars often consist of a mixture of OPC, granulated blast furnace slag, pozzolana, and possibly hydrated lime or hydraulic lime and filler like ground limestone. These binders improve the workability and water retention of the fresh mortar (also due to the use of air-entraining admixtures), but they develop less strength. The availability of granulated blast furnace slag and pozzolana is described in other Technical Papers.

Regulated set cements (known as “Jet Cement” in Japan and “Schnellzement” in Germany) are produced by intergrinding fluoride containing clinker with anhydrite, gypsum, and calcium carbonate. The sulfate content of the cement is 7 to 11% by mass of SO_3, and the carbonate content 3 to 4% by mass CO_2. Due to the amount of 20 to 25% by mass $11CaO \cdot 7Al_2O_3 \cdot CaF_2$ in the clinker and the high SO_3 content of the cement the strength development is comparable to OPC.

The use of hydraulically reactive glasses in the CaO-Al_2O_3-SiO_2 system (e.g. with 45-55% by mass CaO, 30-40% by mass Al_2O_3 and 15-25% by mass SiO_2) has been investigated and can lead to good strength development. Glasses have been developed that can hydrate without activators. The use of aluminophosphate glasses in the Al_2O_3-P_2O_5-H_2O-SiO_2 system has been explored, too. However, strength of these binders often declines after longer hydration time. Furthermore, up to now hydraulically active glasses or aluminophosphate glasses are not available for cement production in relevant amounts.

Blends of gypsum plaster have been proposed as the early-age cementing component, combined with a siliceous component for long-term strength and improvement of durability. Energy required for production of gypsum plaster is only 15% of that required to form OPC clinker, and no decarbonation of limestone takes place. Cements with 20% by mass OPC clinker, blended with gypsum plaster and pozzolanas (silica fume, rice husk ash) or fly ashes, can safe up to 70% in production energy. However, the long-term durability of these types of cement has to be proved. Problems may occur due to the crystallisation of ettringite-thaumasite solid solutions, leading to expansion and deterioration of the concrete. The described cement type has not been technically used in relevant amounts yet.

The calculations below are based on the reference plant data as a starting point (see "key assumptions" in Annex) and refer to the production of cement with 25 to 35% by mass of limestone.

Impact on energy consumption:

thermal: decrease 220 to 600 MJ/t cement for a cement with 25 to 35% by mass limestone

electric: decrease of 12 – 23 kWh/ t cem

CO_2 reduction potential:

direct: decrease 50 to 140 kg CO_2/t cement for a cement with 25 to 35% by mass limestone

indirect: reduction of 6 to 16 kg CO_2/t cem

The main influencing parameters are:

- Type, availability, quality and price (incl. logistics) of the other constituents
- Durability of concrete produced with blended cements
- Impact on electric energy consumption and indirect CO_2 emission depends strongly on the properties of the respective materials
- CO_2 intensity of clinker production
- Transport distances of used materials

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015			8 to 12	
2030			8 to 12	
2050			8 to 12	

Remarks:

- Capital costs are due to extra storage capacity for the other main constituents and the new cements as well as the technical equipment for handling and drying of these constituents.
- Operational cost savings depend on the purchase costs of the other main constituents, reduced fuel costs for clinker production, reduced electricity costs for kiln drives and by-pass, reduced handling and mining costs
- These costs need to be assessed on the basis of individual plants and cement types

Conditions, barriers, constraints:

- Sources, availability, quality (in particular homogeneity) and prices of the other main constituents
- Logistics
- Technical performance of concrete produced with blended cements (e.g. workability, strength development, durability)
- Market acceptance
- Standards and regulations

3.27 Technology Paper No 27: Geopolymer cement

Geopolymer cements 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. The term “Geopolymer” was first used by Davidovits in the 1970s to accentuate the relationship to geological materials.

For a geopolymeric polycondensation suitable materials 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. Chemically geopolymers can be divided into two groups depending on their composition: Materials containing mainly Al and Si (e.g. metakaolin) and materials containing mainly Ca and Si (e.g. blast furnace slag). Geopolymeric binders of the latter group build CSH- and CAH-phases beside the alumosilicate network, which can cause significant variations in quality, e.g. strength development of the binder.

Metakaolin created by sintering the natural clay mineral kaolin was the primary starting material for an alkaline activated polycondensation and exhibits the highest reactivity of all possible materials. Because of high production costs metakaolin will be suitable for special applications only and will not be adapted for broad applications in practise. In addition, the main technical challenge still seems to be maintaining a stable and defined product quality and concrete performance.

Until now, geopolymers have been produced only for demonstration purposes and have only been used in non structural applications, e.g. paving. Techniques for the mass production of geopolymers have shortly been suggested, and a first industrial plant is being built in Australia. The expected CO_2 emission is 300 kg CO_2/t product (or 50% less than a typical CEM II cement). However, this does not take into account emissions due the production of the activators (e.g. sodium silicate). These contribute significantly to the life cycle inventory, but data are not available for these materials. Therefore, based on today’s knowledge, it is not possible to assess the reduction potential of materials like GBFS used as clinker substitute or as a basis for geopolymers.

Impact on energy consumption:

thermal: reduction potential depends strongly on energy demand for activator production

electric: reduction potential depends strongly on energy demand for activator production

CO_2 reduction potential:

direct: reduction potential depends strongly on CO_2 emission from activator production

indirect: reduction potential depends strongly on CO_2 emission from activator production

Alkali-activated systems are claimed to reduce direct CO_2 emissions up to 80% compared to OPC. This does however not include emission from activator and clay production.

The main influencing parameters are:

- Choice and/or production of the reactive starting materials
- Production of the alkaline activators

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015	tbd.	tbd.	-	-
2030	tbd.	tbd.	-	-
2050	tbd.	tbd.	-	-

Remarks:
Currently no real cost figures are available. They need to be determined (tbd.) and will strongly depend on:

- Availability and processing of starting materials
- Costs for alkaline activators
- Development of applications of alkali-activated systems

For a single case (one producer) operational costs being 20% higher than for OPC production are given in the literature.

Conditions, barriers, constraints:

- The properties of geopolymer cements strongly depend on the starting material, its chemical composition, temperature etc. This can lead to variations in the workability (e.g. setting time) and other properties of the concrete like strength development and formation of cracks.
- The durability of the concrete has yet to be demonstrated.
- The reactive components, like fly ash and slag, are industrial waste products and their availability depends on the future of coal fired power plants and the future iron production.
- Operational safety during working with highly alkaline conditions has to be assured.
- Production quantities and costs for the alkaline activator (e.g. sodium silicate) will play an important role on the production of geopolymer cements.

3.28 Technology Paper No 28: Other lower carbonate clinkers (belite clinkers, calcium sulfoaluminate clinker and other)

Ordinary Portland cement (OPC) clinker typically contains 40-80% 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 1350 °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 general opinion, the associated saving in fuel energy is only around 5 % due to the worse heat recovery in the cooler. This must be balanced against the fact that belite clinker is very hard to grind and requires more grinding energy.

The low LSF enables the increased use of secondary CO_2 free raw materials like slags for the clinker production and the therewith saving of natural resources.

In principle, it is also possible to produce belite clinkers by sol-gel or hydrothermal processes at low temperatures between 600 and 900 °C. The resulting belite is highly reactive, but these methods have only been developed on lab-scale and are not suitable for mass production yet.

The most important challenge of industrial belite clinkers is the poor hydraulic reactivity of belite compared to alite, leading to a decelerated strength development that is considered unsatisfactory by most customers. The hydraulic hardening can be improved by addition of OPC or ground alite. Furthermore, the stabilisation of belite and an increase of its hydraulic reactivity can be achieved by thermal treatment (rapid cooling rate) and by foreign elements (such as K, Na, S, B, Fe, Cr and Ba). Rapid clinker cooling has proved to be an economically insurmountable hurdle because the heat of the clinker cannot be recuperated with currently known equipment. Increased alkali contents are a severe disadvantage in concrete technology.

Excess sulphate addition to the raw meal leads to the formation of sulphoaluminate clinker containing yeelimit ($C_4A_3\$=Ca_4Al_6SO_{16}$) as another hydraulic phase beside belite, and furthermore 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. Today, their more general application to concrete is limited to China, where they have been developed and normalised under the name “Third Cement Series” (TCS). Attempts were made in eastern Europe recently to use TCS cements, but the success was limited due to an insufficient strength development. Furthermore, the use of bauxite as raw material makes these cements expensive. The durability is limited e.g. with respect to sulphate attack. Other cements like the so-called Porsal cement are also produced with reduced lime contents but higher contents of alumina up to 15% by mass and minor amounts of SO_3. Porsal cement contains calcium aluminates and calcium aluminate sulfates (CA, $C_{12}A_7$, C_4A_3s) in approx. equal proportions. A procedural disadvantage of all sulphoaluminate cements is the increased tendency to the formation of build-ups during the burning process due to the limited stability of C_4A_3s and internal recirculating sulfate systems in the kiln.

If calcium fluoride is used as a mineraliser in the burning process of belitic fluoroaluminate clinker, the burning temperature can be lowered to 950-1150 °C. The increased tendency to the formation of build-ups during the burning process is the main disadvantage of this method, too. Furthermore, the durability is not satisfactory due to late ettringite formation and with respect to sulphate attack.

Impact on energy consumption:

thermal: decrease 150 MJ/t cli for belite cement

electric: increase 20 to 40 kWh/t cem for belite cement

CO_2 reduction potential:

direct: decrease 60 [kg CO_2/t cem] (for belite cements)

indirect: increase 1 to 28 [kg CO_2/t cem]

The main influencing parameters are:

- Decrease of the CO_2-releasing component ($CaCO_3$) in the raw meal
- Decrease of the fuel consumption due to lower burning temperatures
- Cooler efficiency
- Energy consumption for grinding to achieve a higher cement fineness
- Grindability of belite-rich clinker
- CO_2 intensity of fuel use
- CO_2 intensity of (external) electricity consumption

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015	similar to standard cement plants		8 to 12	
2030	similar to standard cement plants		8 to 12	
2050	similar to standard cement plants		8 to 12	

Remarks:

- For the improvement of strength of belite cements installations for quenching of the clinker may be necessary
- Capital costs can result from extra storage capacity for other raw materials or mineralisers, where required, as well as the technical equipment for handling and drying of these materials

- The operational costs depend on reduced fuel costs for clinker production, reduced handling and mining costs, the possibility to use secondary raw materials, possibly increased electricity costs for grinding of secondary raw material and cement of higher fineness, additional costs for mineralisers, increased costs for bypass and the probably increased time and effort for the removal of build-ups in the kiln
- Operational costs of the production of sulphoaluminate clinker depend on the need, availability and price of additional raw materials like bauxite and mineralisers
- The costs for the industrial production of belite clinkers by sol-gel or hydrothermal processes can not be estimated today because these technologies have only been on laboratory scale yet

Conditions, barriers, constraints:

- Poor early strength development of belite cements
- Market acceptance
- Rapid cooling of belite clinker eliminates efficient heat recuperation
- High risk of coating formation and build-ups in the kiln, e.g. due to high amounts of sulphur or fluoride
- High alkali contents of the clinker

3.29 Technology Paper No 29: Hydrogen from syngas in gasification processes used as fuel for cement kiln burners (precombustion technology for CO_2 capture)

In pre-combustion technologies – as part of Carbon Capture and Storage - (reforming or gasification/partial oxidation based on different fossil fuels) hydrocarbon fuels are processed to produce fuels (mainly hydrogen) which are more or less carbon-free or to reduce the carbon content of hydrocarbon containing fuels. Syngas, which is a gas mixture consisting predominantly of H_2, CO and CO_2, is generated as an intermediate step from fossil fuels like coal or gas. CO is oxidized to CO_2 in a so-called shift reactor. The subsequent separating of CO_2 from H_2 is the main task in pre-combustion capture. Known post-combustion technologies (absorption, adsorption (PSA), membrane processes) can be used to capture the CO_2.

Up to now, pre-combustion technologies have never been used in a cement plant. In other sectors like the chemical, fertilizer and synthetic fuels industry, hydrogen production and separating carbon dioxide from syngas is state-of-the-art, but in most cases designed for smaller gas volumes compared to the requirements of cement kilns. The applicability to the clinker burning process strongly depends on the technical possibility of using hydrogen as a main fuel in the kiln. However, the main disadvantage of pre-combustion technologies is that CO_2 emissions originating from the calcination of limestone will remain unabated.

Due to its explosive properties, pure hydrogen could not be used in existing cement kilns, but could be utilized after dilution with other gaseous fuels or inert gases like nitrogen or steam. Furthermore, the combustion and radiation properties of hydrogen differ significantly from those of the fuels currently used in the cement industry meaning that - even if handling problems could be solved - the clinker burning process would have to be significantly modified and would necessitate new developments in burner and combustion technology.

Impact on energy consumption:

thermal: not available [MJ/t cli.] electric: not available [kWh/t cli.]

CO_2 reduction potential:

direct: < 350 [kg CO_2/t cli.] indirect: / [kg CO_2/t cli.]

As the raw material generated CO_2 is not captured, the CO_2 reduction potential is < 40%.

Cost estimation:

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015	not available	not available	not available	not available
2030	not available	not available	not available	not available
2050	not available	not available	not available	not available

To date, no cost data have been published about a potential application of pre-combustion technologies at the clinker burning process. Nevertheless, there are cost estimations about the specific costs, which could range from 20 to 50 €/t CO_2.

Remarks: The application of pre-combustion technologies to the clinker burning process is unrealistic, so that potential costs will never become importance.

Conditions, barriers, constraints:

- The main disadvantage of pre-combustion technologies is that the raw material generated CO_2 (from the calcination process) cannot be captured. Therefore it cannot be seen as a viable option for CO_2 capture at the clinker burning process.
- To establish pre-combustion technology in cement works the clinker burning process as well as the cement plant as such would need to be modified. At the plant location a separate hydrogen plant with carbon dioxide capture technology would have to be built.
- Today hydrogen production is a commercially available technique. However, no plant has ever been built with a size which is necessary for supplying a cement work with sufficient carbon-free fuel.

3.30 Technology Paper No 30: Oxyfuel technology as part of carbon capture and storage

The Oxyfuel technology relies on the use of oxygen for combustion instead of ambient air. This implicates an air separation unit (ASU) for providing the oxidizer by removing the nitrogen, which is state-of-the-art. This will have a huge impact on the clinker burning process, mainly the energy balance as well as the ratio between the enthalpy flow of the kiln gas and the energy needed for the chemical/mineralogical reactions of the kiln feed. The theoretic flame temperature in the sintering zone rises compared to ambient-air-based combustion. 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. The oxygen concentration in the oxidizer therefore becomes an additional degree of freedom, whereas the optimum level is still unknown for the clinker burning process. Anyway, it will be higher than 21%. That way the carbon dioxide concentration in the flue gas increases significantly up to above 80%. As part of carbon capture and storage technology a fraction of the flue gas stream is discharged to a CO_2 separation, purification and compression facility and then delivered to a transport system. Due to the fact, that the final specifications for the purity requirements are still being discussed in the scientific and regulatory community, the effort of the CO_2 purification can only be estimated nowadays. Still there is very little experience with the Oxyfuel technology in the cement industry. A few plants use oxygen to increase throughput of kilns and enhance the energy efficiency. An actual application in the energy sector has only been realized in pilot scale. By the reason that the Oxyfuel technology in the cement industry is not fully developed yet, the CO_2 emission reduction is within the range of 63 to nearly 100% from today's perspective. In general the Oxyfuel technology influences significantly the burning process and consequently plant units have to be redesigned to the new requirements. On this account the Oxyfuel technology seems to be predominantly an option for new plants.

<u>Impact on energy consumption:</u>

thermal: increase of 90 to 100 [MJ/t cli] electric: increase of 110 to 115 [kWh/t cli]

<u>CO_2 reduction potential:</u>

direct: decrease of 550 to 870 [kg CO_2/t cli.] indirect: increase of 60 to 80 [kg CO_2/t cli]

<u>The main influencing parameters are:</u>

- Achievable CO_2 concentration in the flue gas
- Level of air in-leaks
- Separation ratio of the CO_2 purification
- Energy consumption of the CO_2 separation, purification and compression facility and the air separation unit
- Oxidizer purity (influences energy demand)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	n/a	n/a	n/a	n/a
2030	330 to 360	plus 8 to 10 compared to conventional kiln	90 to 100	plus 8 to 10 compared to conventional kiln
2050	270 to 295	plus 8 to 10 compared to conventional kiln	75 to 82	plus 8 to 10 compared to conventional kiln

Remarks: The cost estimation is based on a clinker capacity of 2 mio. t/a, no inflation. Investment costs have been calculated for the whole Oxyfuel kiln system including oxygen supply and CO_2 purification and compression. Costs for CO_2 transport and storage are excluded. Basically, a huge uncertainty of the cost estimation results from the incompletely developed technology.

It is assumed that a first demonstration plant could come into operation in 2020 at significantly higher costs than described above. A learning rate of 1% per year is considered for the time 2030 to 2050. Operational costs are expressed additional costs compared to a conventional kiln and include mainly additional power costs. Depreciation, interest and inflation are not included in operational costs. The retrofit scenario refers to oxy-fuel operation of the calciner only resulting in a limited CO_2 reduction of about 60% of the total CO_2 emissions from the kiln.

<u>Conditions, barriers, constraints:</u>

- Technology is still on research level for the cement industry
- Integration of energy flows between the additional units (e.g. ASU, waste heat recovery) and the cement plant
- Reduction of air in-leakage
- From a today's perspective the Oxyfuel technology is mainly a solution for new built cement kilns.
- A proposal for a retrofit has been made in an IEA study (Oxyfuel operation of the calciner). This limits the CO_2 reduction to 60%.
- Necessity of additional fuel due to the impact on the chemical-mineralogical material reactions (not completely investigated so far)
- Availability of transport (pipeline) grid and operated storage sites
- Electric energy consumption per ton of clinker will increase by a factor of 3 ("energy or CO_2 penalty")
- Production costs will increase by 40 to 50% related to current cement production costs

3.31 Technology Paper No 31: Post combustion capture using absorption technologies

Absorption techniques are discussed as end of the pipe measures for CO_2 abatement. Principally, up to 95% of the CO_2 can be captured with these techniques. After abatement the CO_2 is purified to > 99% and compressed to > 74 bar for transport to designated storage sites. The pressure, to which the liquefied CO_2 has to be compressed is mainly determined by the transport distance to the storage site. In principle, absorption technologies could be applied both to new and existing plants.

The chemical absorption with alkanolamines is a proven technique in other industry sectors like the chemical or gas processing industries. There, flue gas volumes and absorbent cycles are significantly smaller compared to the application in the cement clinker burning process. Consequently, alterations are necessary to fit this concept for post-combustion flue gas cleaning in the cement industry.

The most common solvent in the chemical industry is monoethanolamine (MEA) which was the first solvent used for amine based CO_2 scrubbing. The central issues concerning amine use are costs and the energy, provided as low pressure steam, to regenerate the sorbent. Advanced amines are commercially available granting lower energy consumption for regeneration. Even more efficient solvents, based on ammonia or activated potassium carbonate are in the development stage. The chilled ammonia process (CAP) shows a promising approach but was not studied for employment within the clinker burning process, so far.

Due to high cost the used solvents have to be regenerated and reused. Regeneration is highly energy consuming; therefore the so-called energy or CO_2 penalty is determined by this process. SO_2 and oxygen play an important role in solvent degradation mechanisms, though more stable and insensitive solvents are mandatory for commercial solutions. Therefore, the absorption technique induces a reduction of SO_2 and particulate matter concentration in flue gases to a minimum (e.g. by wet scrubber and high efficient filter). Depending on the initial level, NO_x concentrations have to be lowered as well as NO_2 also leads to solvent degradation. On the other hand, NO_2 makes only 5 – 10% of total NO_x emissions of cement kilns. For absorbent regeneration, saturated steam between 350 and 450 kPa is needed. Under this circumstance, energy can be recovered from raw gas and cooler vent air of the cement kiln or has to be provided by a separate power or CHP plant. The higher CO_2 concentration compared to power generation does not affect the amount of regeneration energy in significant manner, but allows smaller absorber structures due to less gas volume flow.

Today, absorption technologies are only used on pilot scale in the energy sector; demonstration plants are in planning phase, the first industrial application is expected around 2020. With certain modifications it should then also be available for the cement industry (for new or existing kilns). CCS is an ultimate option to mitigate fossil carbon emissions but one of the most expensive ones, as well. Safe storage is still an open question.

Impact on energy consumption:

thermal: increase 1,000 to 3,500 [MJ/t cli]   electric: increase 50 to 90 [kWh/t cli]

CO_2 reduction potential:

direct: to 740 [kg CO_2/t cli]   indirect: increase 25 to 6 [kg CO_2/t cli]

The main influencing parameters are:

- Type of absorption process
- Available heat, low pressure steam, and shaft work (supplied from co-located power plant)
- Flue gas quality, i.e. sour gas loading (SO_2 and NO_2), particulate matter, O_2 level etc.

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2015	not available	not available	not available	not available
2030	100 to 300	10 to 50	100 to 300	10 to 50
2050	80 to 250	10 to 40	80 to 250	10 to 40

Remarks: The costs provided are rough estimations based on IEA and McKinsey studies as well as own calculations. Investment costs have been indicated as additional costs to the cement plant investment cost. Costs for CO_2 transport and storage are excluded. It is assumed that a first demonstration plant could come into operation in 2020 at even higher costs than described above. A learning rate of 1% per year is considered for the time 2030 to 2050.

Conditions, barriers, constraints:

- Overall primary energy consumption will be very high, likely > 3 MJ/kg CO_2 avoided
- Solvents might be very costly and could degrade to hazardous waste or cause additional emissions
- Comprehensive research and development is necessary to increase the knowledge on absorption technologies
- Availability of transport (pipeline) grid and operated storage sites
- Electric energy consumption per ton of clinker will increase by a factor of 2 to 3 (“energy or CO_2 penalty”)
- Thermal energy consumption per ton of clinker will be doubled
- Extremely high costs compared to current cement production costs (doubling of investment and operating costs is expected)

3.32 Technology Paper No 32: Post combustion capture using membrane processes

Membranes, for separation and absorption, are discussed as future end of the pipe measures for CO_2 abatement. In principle, more than 80% of the CO_2 can be captured with this technique. After capture, the CO_2 has to be purified and compressed up to > 74 bar for transport to designated storage sites. The pressure, to which the liquefied CO_2 has to be compressed is mainly determined by the transport distance to the storage site. In principle, membrane technologies could be applied both to new and existing plants.

Up to now, such membranes are only available on very small or research scale. Further development is expected to need at least 10 years to reach industrial application. Even then there are doubts that it will be technically possible to build membrane reactors for such huge gas volumes as they exist in the cement industry. A major issue is the selectivity of the membranes for specific gases like CO_2.

Two basic membrane types are being considered for CO_2 capture: gas separation and gas absorption membranes. The first group relies on the variations in physical and/or chemical interactions between different gases and the membrane material, with the intention to have one component pass through the membrane faster than another (thus driving the separation process). This technique relies on the diffusivity of gas molecules, and taking advantage of different pressures on either side of the membrane. Various versions of gas separation membranes are available today including ceramic, polymeric and ceramic / polymeric hybrids. Up to now, most of the commercially viable membranes for CO_2 capture are polymer-based. The second group, gas absorption membranes, are micro-porous solid membranes which act as contacting devices between gas flow and liquid flow. While flue gases flow on one side of a membrane, an absorptive liquid is used on the other side to selectively attract certain components. In this case, it is the absorption liquid (not the membrane) that drives the selectivity. Gas separation membranes are manufactured in two different forms: flat sheets and hollow fibres. The flat sheets are typically combined into a spiral-wound element, and the hollow-fibres are combined into a bundle similar to a shell and tube heat exchanger.

Membrane units are small in volume, operationally simple, can be positioned either horizontally or vertically and require little attention once commissioned (low maintenance requirements). Furthermore no regeneration energy is required and no waste streams are generated. They will thus readily fill niche markets for carbon capture such as in offshore and remote locations.

However, membranes also show unfavourable characteristics:

- sensitivity to sulphur compounds and other trace elements
- sometimes low degrees of separation (multiple stages or recycling is necessary)
- polymeric membranes do not tolerate high temperatures

Impact on energy consumption:

thermal: not available [MJ/t cli.]   electric: not available [kWh/t cli.]

CO_2 reduction potential:

direct: > 700 [kg CO_2/t cli.]   indirect: / [kg CO_2/t cli.]

The main influencing parameters are:

- Selectivity
- Permeability
- Partial pressure difference

Cost estimation

(costs for CO_2 transport and storage not included)

Cost estimation	New installation		Retrofit	
	Specific Costs [€/t cl.]	Operational [€/t cli.]	Specific Costs* [€/t cl.]	Operational [€/t cli.]
2015	(45-50 €/t CO_2 av.*)	not available	(45-50 €/t CO_2 av.*)	not available
2030	< 25 €/t CO_2 av.	not available	< 25 €/t CO_2 av.	not available
2050	< 25 €/t CO_2 av.	not available	< 25 €/t CO_2 av.	not available

* Estimations according to UNESCO Centre for Membrane Science and Technology Membranes are not yet available for industrial application in the cement industry

Remarks: To date, membrane technologies are not commercial. Highly specific membrane materials, which are still very expensive, show promising results in laboratory trials. However, intensive research activities are being carried out, so that the costs should fall quickly. It is expected, that within the next 10 years membranes can compete with absorption technologies for CO_2 capture and can provide a cost effective and low maintenance approach for the removal of CO_2 from gas streams.

Conditions, barriers, constraints:

- Gas separation membranes require high operating pressures.
- The separation efficiency and temperature resistance of the membranes have to be improved.
- A scale-up to full-size implementation is required.
- An access to a transport (pipeline) grid and operated storage sites must be given.
- The costs of membrane technologies are extremely high compared to cement production costs.

3.33 Technology Paper No 33: Post combustion capture using solid sorbents

Adsorption processes (as part of Carbon Capture and Storage) operate on a cycling reaction with the basic steps being adsorption and regeneration using physi-sorption, mineral carbonation and/or carbonate looping. 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 loaded bed is regenerated to remove the CO_2. In pressure swing adsorption (PSA), the adsorbent is regenerated by reducing pressure, and in temperature swing adsorption (TSA), the adsorbent is regenerated by raising its temperature. Another regeneration technology, which could lead to an energy saving in the furture, but which is still in an early state of development, is the so-called electrical swing adsorption (ESA). The major types of adsorbents used are activated alumina, silica gel, activated carbons, zeolites and polymeric adsorbers.

A special type of solid sorption processes is the so-called mineral carbonation where the adsorbent reacts with CO_2 to form carbonates (carbonation). The reverse reaction (calcination) is required to release the CO_2 and thereby regenerate the sorbent. This reaction behaviour is known for alkali and alkaline earth metal oxides, e.g. calcium oxide (CaO), but it applies for some other materials too (e.g. magnesium silicates). Up to now, no large-scale adsorption units are known for CO_2 capture from flue gases.

The so-called "carbonate looping" process is a special case of mineral carbonation and 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. 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. The carbon dioxide captured by the sorbent is directed to a calciner for regeneration of the sorbent. For a gas stream rich in carbon dioxide and thereby avoid another purification step the calciner has to be fired with pure oxygen. The gas stream coming out from the calciner shows increased CO_2 concentration and is supplied for subsequent storage. The refreshed sorbent is transferred back to the carbonator and cycled again. Due to deactivation processes, a make-up of the adsorbent is required. The deactivated adsorbent could eventually be used as secondary raw material in cement works, so that synergies between cement and power plants could be achieved. This effect has not been taken into account when estimating the CO_2 reduction potential.

A carbonate looping process under atmospheric pressure can principally be applied to cement works. The loop could be placed between preheater and raw mill. However, the technology is still in the basic R&D phase.

Impact on energy consumption:

thermal: n/a [MJ/t cli] electric n/a [kWh/t cli or cem]

CO$_2$ reduction potential:

direct: ~ 450 to 700 [kg CO$_2$/t cli.]   indirect: not available [kg CO$_2$/t cli.]

Compared to absorption processes, the achievable CO$_2$ capture rates are lower, e.g. 50 - 90%. However, the capture rate could be increased by multi-step adsorption.

The main influencing parameters are:

- Selectivity
- Adsorption capacity

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli or cem]
2015	not available	not available	not available	not available
2030	not available	not available	not available	not available
2050	not available	not available	not available	not available

Remarks: Solid sorption processes are novel technologies for CO$_2$ capture. Up to now solid sorbent processes have not yet reached commercial status for CO$_2$ recovery from flue gases, so that no cost data have been published up to now. Nevertheless, there are cost estimations about the specific costs, which could range from 50 to 80 €/t CO$_2$. In principle, adsorption technologies could be applied both to new and existing plants.

Conditions, barriers, constraints:

- Physi-sorption processes: low energy demand for regeneration; but to date only low selectivity and low adsorption capacities; pre-treatment of gases required.
- Mineral carbonation: large amounts of sorbents are required due to the degradation in sorption activity. It also generates a new waste stream. Heating up of exhaust gas is required (500-600°C), which would result in a high energy penalty.
- Carbonate looping: only in the stage of research and development; sorbents deactivate rapidly, make-up of sorbent required (deactivated CaO can be utilized in the clinker burning process); heating-up of the raw gas required.

Annex I: Key assumptions

Technical and financial calculations are based on following key assumptions.

<u>Cement plants:</u>

Two reference plants based on CSI/GNR data:

Plant 1: weighted average, all kilns, all clinker types

Plant 2: 20% percentile (“new plant”), all kilns, all clinker types

<u>Prices/costs:</u>

- based on Central European conditions (fuel, electricity, investment, operation)
- no depreciation considered in operation cost
- no discount rate
- prices 2007
- no inflation
- fuels / electricity: no future price development estimated
- no cost effect of ET/CDM/JI etc

<u>Learning rates:</u>

- no change for existing, well known technologies
- 1% yearly decrease of investment cost for new technologies (e. g. for CCS)

Annex II: Performance data of reference plants and used costs figures

Performance data of reference plants and used cost figures

Definition of reference plants (Data for 2006)

Parameter		Unit	Reference plant 1 (existing average plant)	Reference plant 2 (new state of the art plant)
kiln type		---	dry precalciner	dry precalciner
clinker capacity		t cli/y	2 mio.	2 mio.
clinker production		t cli/d	6000	6000
cli/cem factor		%	78	71
cement production		t cem/y	2.6 mio.	2.8 mio.
raw meal/cli factor		---	1.6	1.6
fuels: (validated to fuel energy requirement)				
- fossil fuel (coal)		%	90	67
- alternative fuels		%	7	23
- biomass fuels		%	3	10
spec. fuel energy consumption		MJ/t cli	3690	3210
spec. electric energy consumption		kWh/t cem	111	89
relative energy demand for clinker production		%	46%	46%
spec. electric energy consumption		kWh/t cli	65	58
spec. CO_2 emission of electricity production		t CO_2/MWh	0.5 – 0.7	0.5 – 0.7
electric energy cost		Eur/ MWh	80	80
spec. electric energy cost for clinker production		Eur/ t cli	5.2	4.6
gross CO_2 per t clinker		kg CO_2/t cli	866	821
process CO_2 per t clinker		kg CO_2/t cli	540	540
gross CO_2 per t cement(itious)		kg CO_2/t cem	679	600
fuel costs (coal)		€/t	70	70
specific fuel costs (coal)		€/GJ	2.85	2.85
secondary fuel cost	2006	€/t	0	0
	2030		28	28
	2050		49	49
investment costs	2 Mio t/a	€/t yearly prod.		130
		mio. €		260
investment costs	1 Mio t/a	€/t yearly prod.		170
		mio. €		170
investment costs	0.48 Mio t/a	€/t yearly prod.		250
		mio. €		125
operational costs (excl. depreciation)		€/t cli	32	29