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

Dusseldorf, Geneva, 20 March 2017

Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead, Revision 2017

This study was commissioned by the Cement Sustainability Initiative (CSI), a member-led programme 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 increasing energy efficiency and reducing 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 such as the International Energy Agency (IEA), the opinions and views expressed are those of ECRA.

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1 Introduction and objectives

In 2009 the World Business Council for Sustainable Development and the International Energy Agency published a report named the Cement Technology Roadmap which outlined a perspective for the cement sector to achieve long-term CO_2 reduction targets by 2050. This roadmap was based on the CSI/ECRA Technology Papers 2009. Both the Cement Technology Roadmap and the Technology Papers have been used for discussions on the technical potentials for innovation and low carbon development in the cement sector worldwide. In particular, several regional roadmaps for India, Europe, Brazil, and Egypt have made intensive use of these international reference documents.

In 2017 the Cement Sustainability Initiative (CSI) decided to initiate a project together with the European Cement Research Academy (ECRA) to update the perspective of available technologies for CO_2 abatement and energy efficiency in the cement sector. This decision was taken in the light of the discussion and ratification of the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) for the reduction of global warming, a pathway towards low greenhouse gas emissions and climate-resilient development. Furthermore, this update was intended to incorporate information on alternative material and fuel use in the cement industry and to form a new basis for the Energy Technology Perspective (ETP) modelling project of the International Energy Agency (IEA). CSI offered to provide the 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, and the timeline for implementation. CSI commissioned the European Cement Research Academy (ECRA) to propose a list of relevant updates and amendments of new technologies which should be considered and to prepare the updated technology papers. Based on their update and the enhancement of the technology perspective it is intended that the CSI/ECRA technology papers 2017 can again serve as important reference documents for developing further technology roadmaps in the cement sector. The roadmaps for the cement industry shall identify major barriers, opportunities and policy measures for policy makers, industry and financial partners in order to accelerate the research and development of technologies aiming at increasing energy efficiency and reducing greenhouse gas emissions. Such roadmaps shall be agreed by relevant stakeholders such as industry, governments etc.

The present report comprises 52 technology papers as well as 7 so-called state-of-the-art papers. The state-of-theart papers summarise the expected development in the major technological fields, which are thermal energy efficiency, electric energy efficiency, use of alternative fuels, materials and biomass, reduction of the clinker content in cement, new binding materials, CO_2 capture and storage (CCS), and CO_2 use (CCU).

The experience of cement companies joining the Cement Sustainability Initiative (CSI) indicates the importance of systematically assessing the technological potentials for improvement on energy efficiency and CO_2 emissions and of monitoring achieved progress by a

standardised methodology. Therefore, CSI has developed since the year 2000 "The Cement CO_2 and Energy Protocol". It is publically available from the CSI website together with tools for its application by cement companies (www.wbcsdcement.org/CO2Protocol). CSI is relgularly collecting relevant data based on this protocol in its project "Getting the numbers right" (GNR) and presents global and regional results for information to stakeholders.

It was agreed that in the CSI/ECRA Technology papers 2017 estimations concerning the reduction potential and cost shall be related to a reference plant. This reference plant is described based on the most recent data of the CSI GNR-2014 in which technical data from more than 900 cement installations worldwide have been collected. The global average data of all cement plants have been used to define the "typical" cement plant of today. As in the technology papers of 2009, the plant has a clinker capacity of 2 Mio. tonnes per year or 6,000 tonnes per day. In line with the GNR-2014 data an emission intensity of 842 kg CO_2/t clinker and a clinker/cement ratio of 75% are assumed. The key assumptions as well as the data of the reference plant are summarised in the annex of this report. All calculations and assumptions relate to these plants, if not stated otherwise. Investment cost data relate to Central European prices and have to be adapted for other regions in the world, like China, India or Latin America. Fuel and electrical energy cost data is based on information from the 2016 ETP-modelling exercise of the IEA.

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

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European Cement Research Academy GmbH

Dr Martin Schneider   Dr-Ing Volker Hoenig   Dr Johannes Ruppert

2 State of the art

2.1 State-of-the-art Paper No. 1: Thermal efficiency of cement production: State of the art and long-term perspective

Status 2014

Based on the GNR (CSI "Getting the Numbers Right" data collection) of the year 2014, the thermal energy demand for cement clinker manufacturing was 3,510 MJ/t cli (global weighted average for grey clinker, excluding drying of fuels). This figure covers more than 900 kilns, 21% of the cement production worldwide and all technologies. The variations are significant: the 10% best of class (10% percentile) relating to all kilns was approx. 3,000 MJ/t cli. On the other hand, the 90% percentile (90% of the kilns were below this value) amounted to approx. 4,100 MJ/t cli. The variations in the different regions of the world are also significant. The highest energy demand (up to more than 5,700 MJ/t cli) is required for the wet production process, while the lowest figures (down to 3,000 MJ/t cli) are achieved by state-of-the-art pre-calciner 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 figures are usually expressed as short-term (typically 24h- or 36h-average) figures. Depending on the kiln operation and reliability (e.g. the number of kiln stops), and the market situation etc. there is a systematic difference of 150 to 300 MJ/t clinker between annual and short-term levels.

As cement manufacturing is highly capital-intensive, the lifetime of cement kilns is usually 30 to 50 years. 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 continually being modernised, 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 processing allow a significant step towards increasing energy efficiency. For these kinds of retrofits a 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. Through these kinds 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.

Thermal energy demand of the clinker production process

The thermal energy demand for clinker production is ruled by the 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 ener-

gy 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 raw materials or other materials like coal and petcoke, or cement constituents like granulated blast furnace slag. Therefore, the thermal energy efficiency (expressed as used energy related to energy input) of cement kilns is very high compared to many other industrial processes, especially compared to power plants. In consequence, kilns with significantly different specific thermal energy input can be similarly efficient if the heat utilisation for raw material drying, electric power generation, etc. is taken into account.

Criteria

The 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 them are described and assessed quantitatively (concerning reduction potential and costs) in the technology papers. **It must 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 in power consumption.

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 demand for this kiln type in 2014 was 3,380 MJ/t clinker. The respective figure for 1990 was 3,605 MJ/t clinker, equivalent to a reduction of ca. 225 MJ/t clinker over 24 years. In this time period the average kiln capacity increased significantly. While in the beginning of the 1990´s maximum kiln capacities of 5,000 to 6,000 tpd were typical, today maximum capacities reach 8,500 to >10,000 tpd. Such an increase cannot be expected to continue in the future. On the other

hand, the average kiln capacities 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 larger 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 average yearly fuel energy requirement of stateofthe-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

Breakthrough technologies which could lead to a significantly higher thermal efficiency are not in sight.

Based on these assumptions the specific fuel energy demand of clinker burning (as a global weighted yearly average) may decrease from 3,510 MJ/t clinker in 2014 to a level of 3,300 to 3,400 MJ/t clinker in 2030 and to 3,150 to 3,250 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 assumed that no wet, semi-wet, semi-dry or long dry kilns will be in operation anymore, except at 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

Status 2014

The CSI "Getting the numbers right" data collection reported a global average electric energy demand for cement manufacturing of 104 kWh/t cem for the years 2012 to 2014. Before this the energy demand had dropped by 10 kWh/t cem over the previous 12 years. These figures cover more than 900 plants worldwide, and all technologies and clinker and cement types. The variations are significant: The 10% best in class show figures of 85 kWh/t cem and below, while the 90% percentile amounted to 129 kWh/t cem. The variations in the different regions of the world are also significant. It must be stressed that these data represent yearly averages, whereas performance figures are usually expressed as short-term (typically 24h- or 36h-average) figures. Depending on the plant operation and availability (e.g. the 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 a cement plant is usually 30 to 50 years. However, the renewal of assets predominantly takes 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). On the other hand, in many mature markets a trend towards higher product fineness and an increasing demand for secondary abatement technologies have increased energy demand. The technical equipment of existing cement plants is being continually modernised, 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. This has resulted in the continual reduction of specific energy demand over the past years. For further significant steps in reduction of the specific energy demand huge retrofits like changing from cement grinding with ball mills (BM) to highly efficient vertical roller mills (VRMs) or high pressure grinding rolls (HPGRs). For these kinds of retrofit high investment is required. Therefore, they will only be carried out if the market situation is very promising or if the equipment is already very old.

Electric energy demand of the cement process

In the case of dry processing the total electrical power consumption can be apportioned as follows: about 2% for raw material extraction, 25% for raw material preparation, 25% for clinker production plus an additional 3% for fuel grinding, 43% for cement grinding and 3% for packing and loading. These figures already include an average share of 5% for cross-sectoral technologies.

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 and vertical roller mills - for raw material and cement grinding instead of ball mills usually have a lower energy demand. However this has to be seen

against the background of operation reliability and also the cement quality which can be impacted differently according to mill type.

Electrical energy demand is not only driven by equipment but also strongly dependent on product properties. Cement performance has an important impact on power consumption. The higher the cement's strength development, the finer it typically has to be ground, requiring significantly more energy in the mills. Especially in mature markets a development of the product portfolio towards higher strength can be observed. This trend can lead to a rising electrical energy demand although the equipment efficiency improves.

Concerning the clinker burning process, measures which increase thermal efficiency often need more electric power. For example, the installation of modern grate cooler techniques causes a reduction in thermal energy use, but increases the consumption of electrical energy. On the other hand, changing from long wet kiln technology to a modern dry process precalciner kiln saves thermal energy and electrical energy of 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 components (like NO_x or SO_2) requires additional units which require electricity. The use of SCR technology for NO_x abatement for example results in an increase in electrical energy demand of 5 kWh/t cli.

Criteria

The 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 below the minimum energy demand, meaning that "one kWh can only be reduced once". Also, several thermal energy efficiency measures cause an increase in power consumption.

Expected development of state of the art techniques

Based on the CSI GNR data the global weighted average of the specific electrical energy demand for all participating companies has been reduced by 10 kWh/t cement over the past 12 years. This can be ascribed to the above mentioned continual technological update of existing plants but mainly to new installations and large retrofits in emerging markets. On the other hand, a large number of plants are still using equipment installed 30 to 50 years ago.

In theory it can be expected that single particle comminution requires much less energy than largescale industrial grinding equipment. However, bulk grinding involves handling mass flows of up to 1000 t/h, which limits the possibilities to focus grinding forces to individual particles. There are no real breakthrough technologies in sight today, but there is still significant potential to improve the existing technology in order to further increase energy efficiency and to reduce the risk related to substitution of existing equipment. This involves high pressure grinding but also special fine grinding applications. Besides the efficiency of the installed equipment, the flexibility of production is of increasing interest with regard to the intermittent availability of renewable energy sources in some world regions. By designing production facilities like grinding plants in a way that they can be easily started and stopped the use of renewable energy can be maximised. This will not reduce but rather slightly increase the absolute power demand, but reduce the indirect CO_2 emissions of power generation.
With regard to the thermal process it can be expected that environmental requirements will increase and that the cement manufacturing process therefore therefore have to be enhanced by more and more units for emission reduction, resulting in a significant increase in power consumption.

Based on these assumptions the specific electric energy demand of cement production may decrease from 104 kWh/t cement in 2014 to a level of about 100 kWh/t cement in 2030 and to 90 to 95 kWh/t cement in 2050 on average. But this strongly depends on market developments and the required product fineness. Furhtermore, this estimate excludes new very electricity-intensive technologies which are being discussed for future implementation in the cement industry, like carbon capture technologies (CCS).

If CCS will be applied on an industrial scale, the power consumption of cement manufacturing will increase significantly. As described in the respective technology papers, oxyfuel as well as post-combustion technologies will require high power consumption for oxygen production in an air separation unit, the regeneration of absorbent agents, and the separation, purification and compression of CO_2. Therefore, CCS would increase power consumption by 50 to 120% on plant level. Assuming a CCS implementation degree of maximum 20 installations in 2030 (see state of the art paper 5 on CCS, equal to capacity of 40 Mt/year clinker in 2030) or about 1% of clinker capacity and up to 20% in 2050, an additional power demand in cement production (as a global average) of plus 1 kWh or 101 kWh/t cement is expected in 2030 and 105 to 110 kWh/t cement in 2050 respectively. These estimated global averages

could further increase by 5 to 15 kWh due to the demands of additional emission reduction units and increased product finness.

2.3 State-of-the-art Paper No. 3: Alternative fuels, raw materials and biomass used in the cement industry: Long-term perspective

Status 2014

Based on the GNR (CSI "Get the Numbers Right" data collection) data for the year 2014, the use of alternative fuels on a global level was 16% of the total fuel energy demand for cement manufacturing. Almost 6% of the 16% was covered by biomass and the remaining 84% was provided by conventional fuels, mainly coal. The variations on a global level in the different regions were significant: the 10% best of class (90th percentile) covering all kilns reached a substitution rate of more than 30% for alternative fuels without biomass and 17% for 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 60% for an industry sector and up to 95% as a yearly average for single cement plants. As the fuel-related CO_2 emissions are about one third of the total emissions (306 of 842 kg CO_2/t cli for the reference plant). The CO_2 reduction potential can be significant if pure biomass use is assumed. Besides 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 25 times that of CO_2. The extent of this effect strongly depends on the waste properties and the local conditions of waste treatment.

The utilisation of alternative calcium-containing raw materials which are already de-carbonated offers a chance to reduce process-related CO_2 emissions from the de-carbonation of raw materials as well as CO_2 emissions from the fuel required for decarbonation. Such de-carbonated raw materials are often already used when available locally and when they are suitable with regard to the required composition of the raw meal.

Fuel types

The CO_2 reduction potential of alternative fuels containing biomass is principally based on two direct effects: firstly, many alternative fuels exhibit a certain biomass content of which the CO_2 emission factor is accounted zero. Secondly, most fossil alternative fuels have lower CO_2 emission factors related to their calorific value than coal or petcoke. Furthermore, there can be an indirect effect of emissions being reduced if wastes are used in a cement plant instead of being landfilled or incinerated in separate installations with corresponding additional emissions. 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 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 tex-

tiles, paper, etc.). In principle, it is also possible to use other organic material as fuels, like natural wood or certain grass types (e.g. miscanthus), other fast-growing species or cultivated green algae. These materials are not wastes and have to be cropped especially for later use as fuels. Today this is not globally relevant for the cement industry for economic reasons.

Raw materials

The local availability of suitable de-carbonated raw materials is often limited. Significant reduction potentials can probably only be achieved at very few sites with specific alternative raw materials, e.g. blast furnace slag, lignite ash, concrete crusher sand, carbide sludge, aerated concrete meal or lime residues from sugar industry. The efficiency is determined by the de-carbonated fraction which may vary strongly even for the same material, e.g., in case of concrete crusher sand. Different uses of the same material restrict the available amount or may make their use more expensive. E.g. granulated blastfurnace slag is important also in terms of the reduction of CO_2 emissions as a constituent of cement (see State-of-the-art Paper No 4). Further preparation steps, e.g. in the case of concrete crusher sand, may improve the quality of the material but also enlarge the costs and the environmental efforts for the material supply. Alternative raw materials from wastes require careful testing with regard to their suitability for use in the clinker production process.

Criteria

- In principle, cement kilns can utilise 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 to 18 GJ/t). For the main firing of the cement kiln an average calorific value of at least 20 to 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 also allows 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 demand per tonne of clinker. Therefore, it is possible that although the use of these fuels leads to higher energy demand, CO_2 emissions are reduced nevertheless.

- The penetration of technical and operational experiences within the cement industry is a major criterion for the use of alternative fuels on a global level as cement kilns operate significantly different at higher rates of substituten of conventional fuels by alternative fuels.

- Higher substitution rates will normally require that waste legislation in the given region restricts land filling or introduces specific pricing and thereby allows a controlled waste collection, waste 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 the need to continuously further reduce CO_2 emissions 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 to a growing extent be more difficult for the cement industry to receive significant quantities of these materials at acceptable prices.

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, the higher the fuel price. On the other hand, in some regions alternative fuels like e.g. saw dust or rice husk are more expensive (related to their calorific value) than e.g. petcoke. 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 this, it is expected that there will still be an economic benefit for cement plant operators to utilise alternative fuels, especially fuels containing biomass, but the payback time may become much longer compared to today. This development will of course be significantly influenced by CO_2 prices.

Development of state-of-the-art techniques

It is very difficult to predict the levels for the future substitution of conventional fuels by waste or biomass fuels due to the large number of technical, economic, political and societal criteria described above. It has to be stressed that the achievement of higher stubstitution rates depends more on political and legal aspects than on technical ones. Nevertheless, a precautious estimation points to the possibility that in developing regions the substitution rate could raise up to 15% or 20% in 2030, whereas in developed regions a substitution rate on the cement industry sector level of 60% should be possible. Globally this could lead to an average level of about 35%. In 2050 the estimations predict a substitution of 30% in developing regions and 70% in developed regions, corresponding to about 45% 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 the social acceptance of co-incineration of waste in cement plants are achieved. Furthermore, it has to be assured that sufficient quantities of suitable 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

Status 2014

Based on the GNR (CSI "Get the Numbers Right" data collection) data for the year 2014, the clinker-to-cement ratio on a global level was 75%. Based on a total cement production of about 4,200 Mio. t, this was equivalent to the use of more than 1,000 Mio. t of materials which partially substitute clinker. The variations of the clinker-to-cement-ratio in the different world regions were significant in 2014: The 10% best of class (10% percentile) of all companies covered by the GNR showed a clinker-to-cement ratio of 65%, whereas the 90% percentile was nearly 88%. An average clinker-to-cement ratio of 58% has been reported for China based on the use of significant amounts of fly ash and slag. In Europe, for example, the average was 73%, the 10% percentile of the clinker-to-cement ratio being 66%. From a technical point of view, lower weighted average values are possible. Materials like blast furnace slag, fly ash, natural pozzolanas or limestone meal are available globally in respective quantities; however, regional availability is very different and limits the use of such materials. Regional differences also depend on the question of how much cement is used finally in concrete products according to regional standards.

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) exhibits 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 exhibit 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 the 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 particular local relevance. Sililca fume, a byproduct in the production of silicon and 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 sil-ico-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 the increasing proportion of pozzolana. They show a better workability, a higher long-term strength and in particular 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.

Recent developments use synergetic effects of optimised combinations of calcined clays and ground limestone as supplementary cementitious material. It is stated that the co-addition allows a clinker reduction of up to 50% maintaining similar performance to existing cements.

Criteria

The use of other constituents in cement besides clinker depends on six criteria:
The availability, properties, and prices of the materials, the 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. Currently, an estimated amount of 270 Mio. t/a GBFS is produced worldwide. Fly ash is produced in coal-fired power plants; the current worldwide production is estimated at about 800 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 35 Mio. t of 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.

The prices of materials which can partially substitute clinker depend on the local situation. An increased demand and/or the competition of different applications (e.g. cement, concrete, others) can lead to a rise in prices.

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.

In any case, all cement constituents must comply with certain qualities like those given in the standards; otherwise the quality and performance of the corresponding mortars or concretes might be significantly impaired.

The market acceptance will strongly depend on the performance of cements with a lower clinker-to-cement-ratio and requires cement producers and cement users to introduce these cements to the market in a joint effort.

Expected development of the reduction of clinker content in cement

The current availability of GBFS, FA, and pozzolana is estimated to be more than 1,000 Mio. t/a, while the cement consumption is about 4,200 Mio. t/a, with a significant further increase expected in certain regions. Assuming a 10% average use of limestone as supplementary cementitious material, a reduction of the worldwide clinker content to about 60% seems to be possible. For further reduction of the clinker-to-cement-ratio calcined clays must be taken into account. The worldwide availability of raw clays is comparably high. However, a scenario for their use in the cement industry must take into account that certain quantities of these materials do not exhibit the required quality.

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, materials suitable for partial substitution of clinker are used in notable amounts for other purposes like concrete production instead of cement production. Under these conditions it can be estimated that by 2030 the clinker-to-cement-ratio might be 65% to 70% and 60 to 65% by 2050.

For this scenario, larger transportation distances will be required, which will lead to additional costs, energy demand and CO_2 emission for the transport. The described interrelations show that the mentioned "classical" cement with main constituents other than clinker has a significant contribution to the reduction of CO_2 emissions, but limited potential for further reduction. The role of new types of cements/binders is still open. However, from a mid-term perspective there is no binder system with the potential to replace Portland cement clinker-based cements on a larger scale.

2.5 State-of-the-art Paper No. 5: New binding materials: Long-term perspective for application in the cement industry

Alkali-activated binders

Suitable materials are alumosilicates which can be of natural (metakaolin, natural pozzolana) or industrial origin (fly ashes, granulated blast furnace slags - GBFS). In any case the availability of these materials is limited. Furthermore, these alumosilicates are currently being used for conventional cement production for further reduction of the clinker-cement-ratio. The high sensitivity to different water contents makes alkali-activated binders difficult to use in ordinary concrete applications, especially since concrete aggregates are often wet to different extents, so quality control may well be the overriding problem in practice. Operational safety while working with highly alkaline activators (sodium hydroxide or alkali-silicates) has to be assured, which might cause some difficulties on the building site. In comparison to classical cements and concretes the properties of alkali-activated binders very strongly depend on the starting material properties, their chemical composition, temperature and moisture etc. Currently, no real cost figures are available, but some case studies reveal that costs tend to be higher than for conventional concrete. This mainly depends on the activator's costs. A first industrial plant has been built in Australia. Reportedly, durable concretes can be produced with up to 60 MPa and higher strength (with heat curing) and with high temperature resistance (due to less chemically bound water) for pavers, pipes etc. and even for pavements. In summary, even if technical barriers might be overcome, alkali-activated binders will only be able to be produced regionally in limited quantities for niche products.

Cements based on the carbonation of calcium-silicates

The raw materials (limestone and quartz) are globally available in abundance. Low lime calcium-silicates, e.g. wollastonite (C/S = 1), can be burnt at about 250 °C lower burning temperatures in comparison to Portland cement clinker in conventional cement plants. The clinker is non-hydraulic, which makes transport and storage easier (insensitive against moisture). Water only enables a certain workability of the fresh concrete for casting and is mainly removed during CO_2 curing. It can be collected and reused. Due to the non-hydraulic properties of the binder a very long workability of fresh concrete and an almost complete recycling of residues is possible. The active carbonation of the silicates via CO_2 rich atmosphere at ambient gas pressures serves as an effective CO_2 sink. Operational safety during working with CO_2 has to be assured. Therefore, such technology seems to be rather suitable for precast plants near CO_2 emitters using CCU (carbon capture and utilisation) for the production of unreinforced precast elements. Concete properties are adjustable via the composition and especially by the duration of CO_2–curing. Reportedly, concretes with up to 80 MPa with sufficient durabilty (e.g. railway sleepers, pavers) can be produced. Currently no real cost figures are available. Reportedly, a commercial launch is planned in the near future in some key markets in North America and in Europe for the manufacturing of concrete elements such as paving stones, roof tiles and concrete blocks. In the mid-term view this binder system has the

potential to substitute conventionally produced unreinforced prefabricated elements to a greater extent.

Cements based on pre-hydrated calcium-silicates

The essential raw materials (e.g. limestone, quartz) are globally available in abundance. The synthesis of non-hydraulic calcium-hydrosilicates by hydrothermal process as precursors is known from calcium-silicate production. The conversion to hydraulically active calcium-hydrosilicates via heating (partly dehydration and amorphisation) is also a known behaviour and feasible in classical kilns. Currently no real cost figures are available for such a procedure.

A new approach is the activation of autoclaved non-hydraulic CHS-precursors (e.g. α-C2SH) phase by intergrinding with unreactive silica-rich substrates such as quartz to generate a core-shell product with a hydraulically active rim. The autoclave and activation-grinding process differs widely from the conventional cement manufacturing process. The core-shell product with a very thin, amorphous reaction product on top of a crystalline or non-crystalline silicate requires other measurement techniques for production and quality control than those known for classical cement. Thus, new analytical methods are under development and must be further optimised. Reportedly, the binder is compatible with conventional cements (blending possible) and ordinary admixtures. The fresh concrete behaviour is nearly the same as for conventional concrete. The hydration characteristics are almost the same as for classical CSH-based systems. The strength development and the final strength vary in the same range as conventional cements (cement standard strength up to 80 MPa). During hydration a matrix with a very low permeability (without $(CaOH)_2$) is formed very early, which might be advantageous for high durability issues. A high CO_2 saving potential is induced by the use of a filler core such as quartz instead of complete reactive clinker particles. Currently no real cost figures are available for such a procedure. There is still a large potential for optimisation, as the principles of activation grinding are very different from experiences with "simple" comminution in ball or vertical mills. A first industrial-scale plant is planned for 2017/2018.

Cements based on belite

Belite cements are based on the same and very abundant raw materials also needed for traditional cement production. They can be produced with a lower lime saturation factor (LSF) and at lower temperatures around 1350 °C in conventional cement plants. The higher hardness of belite in comparison to classical clinker requires extra energy for grinding.

Belite clinkers have a lower hydraulic reactivity compared to alite, leading to a decelerated strength development that is considered unsatisfactory by most customers. An increase of its hydraulic reactivity can be achieved by thermal treatment (rapid cooling rate) and by the incorporation of foreign elements (such as K, Na, S, B, Fe, Cr and Ba) in the clinker. 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. The properties of concretes made with

belite cements are well known. Concretes with belite cements exhibit a dense microstructure (less portlandite) and high long-term strengths as well as a very moderate development of hydration heat. Due to the relatively low strength development in combination with the relatively low CO_2 saving potential, such cements are only used for regionally-sepcific applications (e.g. massive concrete structures, dams). Furthermore, the properties of belite cement can also be achieved by the use of conventional cements, e.g. CEM III. Therefore the potential to substitute Portland cement clinker on a large scale is considered as very limited.

Cements based on (belite) calcium-sulphoaluminate clinker

In comparison to Portland cement clinker, for the production of belite calcium-sulfoaluminate clinker (BCSA clinker) higher amounts of alumina and sulphatecontaining raw materials are necessary, which makes these cements more expensive. The clinker can be burnt in conventional Portland cement plants at 150 to 200 °C lower sintering temperatures. 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 ye'elimite (C4A3$) and internal recirculating sulphate systems in the kiln. BCSA clinkers are more friable and therefore easier to grind. BCSA cements mainly contain the phases belite (C2S), ye'elimite and gypsum. During hydration, ettringite and aluminium hydroxide (high early strength) as well as CASH-phases (later strength) and monophases are formed. The strength development and concrete durability depends on the composition of BCSA cements (aluminates: high early strength; silicates: high late strength). Concretes usually show a high sulphate resistance but often less carbonation and chloride migration resistance. Due to low alkalinity BCSA clinker is not a good activator for conventional supplementary cementititous materials. Basically comparable properties as known for Portland cement concrete can be adjusted. At present less than 2 Mio. t/year are produced and used mainly in China for structural and non-structural concrete. Small cement quantities are also produced in Europe, which can be applied according to technical approvals. In the mid-term view this binder system has the potential to substitute Portland cement clinker-based binders to a few percent.

Expected development of new binding materials

A lot of interesting approaches and the further development of existing concepts will be applied increasingly in order to substitute a small share of cements based on Portland cement clinker. However, from a mid-term perspective none of the new binding materials presented in this paper possess the potential to replace cements based on Portland cement clinker on a larger scale. The new binding materials and systems presented will develop and enter the market for niche products with regional importance, e.g. for repair mortars, quick cements and other cementitious preparations. Their use and further development depends among other things on legal framework, standardisation processes, CO_2-emission costs, market acceptance etc. Some similarities to Portland cement properties might be of help in developing and understanding the key parameters that determine the long-term performance of the binders.

An increasing diversification of the binder market will generate new products and new requirements for:

- Manufacturing and construction processes (e.g. increase of prefabricated constructions, development of corrosion-resistant reinforcements, etc.)

- Test methods (simulation of complex mechanisms, development of new techniques)

- Education (higher degree of specialiaation required for application)

- Standardisation (reliable application).

2.6 State-of-the-art Paper No. 6: Carbon Capture and Storage (CCS): Long-term perspective for application in the cement industry

Status 2016

CO_2 capture and storage (CCS) is an approach to CO_2 abatement, by which CO_2 arising from large point sources like power plants and industrial processes is captured and stored away from the atmosphere for a very long period of time. After the power sector, the cement industry is one of the most important CO_2 emitters. Therefore, the application of CCS technologies is also being discussed in the cement industry. Up to now, only a few results from pilot trials or industrial scale trials at rotary cement kilns are available. Besides technical aspects, economic feasibilty will be decisive for future applications of carbon capture in the cement industry. At the moment, the costs for CO_2 capture amount from >50 to >70 €/t CO_2 avoided. However, it is expected that the cost will decrease to ≤40 €/t CO_2 avoided in the future according to the technical and scientific progress. This estimate has been made for a reference cement plant with a clinker production capacity of 6,000 t/day or 2 Mio. t/year (see Annex I and II), which is a larger reference capacity compared to a previous study of ECRA and IEAGHG in 2013. The above figures do not include additional costs for CO_2 transport and storage.Today, most capture technologies are still in the stage of research and require more investigation regarding the technical and economic feasibility before industrial–scale installations can be realised at the clinker burning process. Up to now, only few operational experiences from small-scale projects are available in the cement sector.

Cement CO_2 capture technologies

According to the current state of knowledge, some CO_2 capture technologies seem to be more appropriate for a potential application at cement kilns than others:

Post-combustion technologies are end-of-pipe measures which would not require fundamental changes in the clinker burning process. Therefore, these technologies would be applicable not only at new kilns, but also for retrofits at existing cement kilns. The most advanced post-combustion technology is chemical absorption because operational experiences are available from several industries, and high abatement rates also seem to be achievable. These technologies are being tested in the cement industry at pilot-scale level. However, the significant additional costs of the post-combustion technologies are a major barrier to their full-scale application. In the long run, membrane technologies could also be a candidate for post-combustion CO_2 capture at cement kilns if membranes with sustained high separation performance could be found. Other post-combustion measures, e.g. physical absorption or mineral carbonation, seem to be less feasible from today's point of view due to a lack of selectivity or the required huge mass streams of mineral sorbents.

The calcium looping process is another interesting option for CO_2 capture and is the subject of several ongoing research activities. As a tail end process, synergies could be generated in the cement industry if the deactivated sorbent could be utilised as an alternative raw material

in the clinker burning process. A modified version of the calcium looping process, which would be integrated in the preheater of a rotary cement kiln, is still subject to basic research and development.

Oxyfuel technology is currently seen as a more economic candidate for CO_2 capture at cement kilns although it is still very costly. The use of oxygen instead of air in the cement kiln firing would result in a comparatively pure CO_2 stream, which could be supplied to the transport and storage infrastructure with less effort for purification. Certain operational experiences are available from cement kilns in the USA and Europe which were operated with oxygen enrichment to increase the kiln production capacity. Furthermore, oxyfuel technology has been investigated at power plants, so that some of the results obtained may be transferred to cement kilns. However, there are also current research activities in the cement industry (ECRA CCS project, CEMCAP project) investigating options for the design of an oxyfuel clinker burning process and the impact on product quality and costs. A study, which was financially supported by the IEA, proposed a retrofit option in which only the precalciner of a cement kiln would be operated in oxyfuel mode. Similarly, ongoing research on separate flash calcining is focused on capturing CO_2 from the calcination process (e.g. EU-Project Leilac). In these two concepts the other main plant components (kiln, cooler, raw mill) would be operated conventionally and don't require high efforts for the improvement of seals. Furthermore, the quality of the clinker product would not be affected. On the other hand, the capture efficiency is significantly lower (about 60 % to 70 %) compared to full oxyfuel operation of the clinker burning process (about 85% to 95%).

Pre-combustion technologies have also been assessed in the ECRA CCS project but exhibit only a limited potential as a capture technology for the cement industry because the capture process would be limited to only CO_2 from fuel combustion (less than 35%).

In addition, research on CO_2 capture by photosynthesis (e.g. with algae) or photo-catalytic reduction of CO_2 has been initiated but is today still at a pilot stage.

The transport and storage of huge amounts of CO_2 is still an unresolved question because the required infrastructure is not yet available in most countries of the world. While technological solutions seem to be feasible, the cost, legal framework and social acceptance are in many regions perceived as a major challenge for any industrial application. It remains an open question if besides long term CO_2 storage a reuse of CO_2 (see State of the Art Paper S7) could be an adequate alternative.

Criteria

- CO_2 capture technologies can be realised when the full chain of CCS or integration with processes for CO_2 reuse are available

- Technology must be available on an industrial scale

- Funding for significant investment costs

- Economic and political conditions must allow the application of CCS in the cement industry without the high risk of carbon leakage due to significant additional operational costs

- For CO_2 storage a transport infrastructure (pipeline network) and access to suitable storage sites are required

- Public acceptance must be ensured

- The legal requirements for CO_2 transport and storage, monitoring and verification and for the licensing procedures have to be resolved

Expected development of cement CO_2 capture

Up to now, only a few pilot trials and one industrial-scale demonstration of post-combustion capture processes have been carried out in the cement industry. Several feasibility studies, which have been carried out in the past years, show the big challenges for the cement industry regarding the dissemination of carbon capture technologies. From a technical point of view oxyfuel and carbonate looping technologies will probably not be available for the cement industry before 2020. However, it can be expected that in this period more research projects or pilot tests will be performed in order to gain practical experiences with these new technologies. First demonstration projects are currently being discussed, but have not been decided on so far. Therefore, it is realistic to expect that only one or two more demonstrations for cement CO_2 capture will be initiated by 2020. In the medium-term it is assumed that between 2020 and 2030 further full-scale demonstration projects will be realised. Against this background, the total CO_2 reduction will still be low. A rough estimation based on 10 to 20 projects globally at rather large kilns (average clinker production capacity of 6,000 t/day or 2 Mio. t/year) and a reduction efficiency of 80 %, predicts an overall reduction of max. 0.025 Gt/a. After 2030, CCS could become commercially implemented leading to significantly higher abatement rates if an appropriate political framework would support it and social acceptance could also be achieved for the CO_2 transport and storage.

A basic scenario postulates that the political framework will not impose similar carbon constraints for the cement industry on a global level and will therefore allow a shift of production into countries or regions with less carbon constraints. Consequently, due to the very high costs, CO_2 capture will only be applied in the cement industry if the political framework effectively limits the high risk of carbon leakage. As CCS requires a CO_2 transport infrastructure

and access to storage sites, cement kilns close to suitable storage sites and in industrialised regions could be connected to the grid while plants outside of these areas would be excluded. Although a lot of research is being carried out aiming at exploring CO_2 storage sites worldwide, the technical availability and social acceptance of CO_2 storage - at least in Europe and North America - is still critical and an estimation of its 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.

In a second scenario, which seems very improbable from today's perspective, it is assumed that a similar global political framework would apply to a high percentage of global cement production, carbon leakage would be more or less prevented and the implementation of CCS technologies would politically be facilitated. Provided that the open technical questions are solved, new kilns could be equipped with carbon capture technologies to a larger extent than existing ones (retrofits). Assuming a cement kiln lifetime of 30 to 50 years, 20 to 33% of the existing kilns will be replaced by new ones within 10 years. Due to higher specific costs, it is expected that kilns with a capacity of less than 2500 to 3000 tonnes per day (tpd) will not be equipped with CO_2 capture technologies. Assuming a 50% share of big kilns on new capacity in the future and a (hardly realistic) implementation rate of 100% for new big kilns, between 2030 and 2050 a maximum 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 post-combustion technologies. This means that CCS implementation would 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 available. The probability of such a scenario will remain highly dependent on political and technical prerequisites such as the social acceptance of this technology, an effective prevention of regional and international carbon leakage, a very high demand of renewable electrical energy for CO_2 capture, the availability of save CO_2 storages with sufficient capacity as well as extensive deployment of CO_2 use options (see following State-of-the-art Paper No. 7).

2.7 State-of-the-art Paper No. 7: Carbon Capture and Use (CCU): Long-term perspective for application in the cement industry

Status 2016

An important option for significant CO_2 reductions from the cement industry is CCS, carbon capture and storage. If the captured CO_2 is used as a feedstock for the generation of products with an added value, the concept is called carbon capture and reuse (CCR) or carbon capture and use (CCU). Currently, the reuse of CO_2 is the subject of many research projects and efforts to advance the integration of carbon use in different industries. CCU technologies are not specific to the cement industry, but can be linked to any CO_2 capture process. The application of a CCU process to a cement plant burning biomass fuels in the rotary kiln (BCCU: biomass based CCU), could also produce negative CO_2 emissions as long as the biomass-based carbon is not released to the atmosphere.

Although the markets for CO_2 use are limited and a business case is not yet given, the concept of CCU and the use of carbon in products should not be underestimated as an alternative to the geological storage of CO_2, which triggers resistance from the public in many countries.

For most reuse technologies an upstream CO_2 capture process has to be applied producing a CO_2 gas stream with the required purity. However, there are also technologies where the capture and reuse of CO_2 are integrated into one process step. Ideally, the reuse of CO_2 could be carried out on the same site or in the vicinity of the capture plant, so that it is not required to develop an extensive transport infrastructure previously.

Carbon use technologies

The most important utilisation of captured CO_2 is currently enhanced oil/gas recovery (EOR). There are already numerous applications in oil producing countries and it is economically viable - depending of course on the oil/gas price. The objective should not only be to boost the oil production by the injection of CO_2 (tertiary recovery) but also to store the CO_2 at the end of the oil/gas production.

Another concept for capture and storage or utilisation is the so-called mineral carbonation process, in particular with Mg- or Ca-silicates. Special industrial wastes could also be used for this process. It is not required to use a pure CO_2 gas stream to achieve a sufficient reduction rate. However, the reaction kinetics are slow and in most cases a pre-treatment of the silicates is needed. The reaction products, e.g. stable $CaCO_3$ or $MgCO_3$, could be used as a building material or could also be stored underground. In both cases the captured CO_2 would be safely removed from the atmosphere for very long periods. The disadvantages of mineral carbonation technologies are the huge mining activities and the handling of enormous mineral masses which are associated with the mineral carbonation process.

Another option for the reuse of captured CO_2 are chemical reactions with hydrogen (hydrogenation) to produce products like fuels, chemicals, polymers, etc. The hydrogen has to be produced by water electrolysis using renewable electrical energy. Oxygen as another reaction product of the water electrolysis could be used for an oxyfuel fired cement kiln. If methane is produced, the concept is called power-to-gas (PtG); in the case of liquid reaction products (methanol, hydrocarbons, etc.) it is called power-to-liquids (PtL). A more general name subsuming the different options for catalytic reactions between CO_2 and H_2 is power-to-X (PtX). These and other options for the production of basic chemical products from captured CO_2 as an alternative source of carbon as a raw material, the technical feasibility of production processes at large scale, energy requirements and the economics are currently the subject of intensive research.

The capture of CO_2 and its reuse for the production of fuels could be an interesting approach for the storage of excess energy from renewable sources. Although the fuels are burned and again generate CO_2 as a combustion product, the total CO_2 emissions from the cement industry and traffic (where the fuel would be used) would be reduced. An important advantage for this option is that the markets and the applications for gas and liquid fuels are already there and the storage capacities (especially the natural gas grid) are very high.

Another example of CCU for the production of a chemical is the so-called Skymine process. In this case a CO_2-containing gas stream is treated in an absorber tower with NaOH solution to produce sodium-bicarbonate ($NaHCO_3$). An industrial-scale plant has already been installed in a cement plant and is in operation. The produced $NaHCO_3$ and other co-generated products can be sold. However, NaOH is an additional material input required for this process.

The reuse of CO_2 for the production of microalgae is an option which has already been investigated in pilot projects with flue gases from cement kilns. An advantage of this technology is that the CO_2-containing flue gas could be used without further purification. Trace components like NO_x do not seem to have adverse effects on the algae growth. The produced algae could be used e.g. as fish food or as third generation biofuels. The integration of nutrient cycles, e.g. of phosphorus, is an important element to achieve sustainable solutions with a potential for scale up. A significant disadvantage is however the huge space requirement of the algae farms. The electricity for all process steps has to be sourced from renewable energies – otherwise this option would result in a net increase of the CO_2 emissions.

It has to be mentioned that in addition to the discussed reuse options other technologies are also being investigated, e.g. electrochemical or biochemical conversions. However, these technologies are in an even lower stage of development and exhibit a lower technical readiness level. Furthermore, there are also small markets for the use of pure CO_2 gas streams in the food sector, as supercritical solvents, etc.

Criteria and expected development of carbon use

All reuse technologies are in a very early stage of development so that cost numbers are difficult to estimate. In general it can be said that except for EOR, all reuse technologies are not yet economically feasible.

Today it is hardly possible to predict how the different CO_2 reuse technologies will develop over the next decades. Much depends on the political boundary conditions, e.g. energy taxes and duties, the availability of renewable energy at low cost, the cost of CO_2 certificates and other regulatory issues (e.g. regarding the alternative storage of CO_2), and the cost of the traditional primary carbon resource materials like natural gas and oil for chemical products. To achieve competitive production factors like the consumer's willingness to pay for a certain product and the environmental benefit of using CO_2 as a carbon resource also play an important role.

3 Technology Papers

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

Certain constituents that 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. Acting as fluxing agents, even in small quantities they can lower the viscosity of the melt at the same temperature and generally also lower the temperature at which the clinker melt begins to form.

Mineralisers are substances promoting the formation of clinker compounds without participating in the formation reactions. Since many substances act as mineralisers as well as fluxing agents, it is usually not possible to differentiate between them. Fluorides are particularly effective. They strongly promote the formation of tricalcium silicate (C_3S) and reduce the lower temperature limit of its stability range.

The fuel energy demand is reduced if the sintering zone temperature required for clinker formation is lowered, e.g. by using mineralisers. From model calculations for a modern kiln it has been estimated that a reduction in sintering temperature by 200 K may 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 by about 150 K. Furthermore, the addition of up to 1% by mass of calcium fluoride (CaF_2) lowers the dissociation temperature of calcium carbonate resulting in a total reduction potential of up to 180 MJ/kg cli. However, the saving potential of this measure is limited. Though the addition of small quantities of mineralisers can improve product quality, larger quantities will affect quality and the kiln operation (increased coating formation).

Additional costs of mineralisers and/or fluxing agents need to be considered carefully. In partucular, the most frequently used CaF_2 is highly cost-intensive, so that fuel savings commonly do not outweigh the additional costs. However, if alternative raw materials containing fluoride are used, costs can be negative, but in general, the availability of such materials is limited.

Impact on energy efficiency

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

CO_2 reduction potential

direct: decrease of 4 to 16 [kg CO_2/t cli]   indirect: increase of up to 0.5 [kg CO_2/t cli]

<u>Material input</u>

mineraliser/fluxing agent   0.25% of F$^-$ by mass in clinker

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

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

<u>Cost estimation</u>

Cost estima-tion	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	not applicable	0.04 to 0.33 decrease
2030	not applicable	not applicable	not applicable	0.06 to 0.45 decrease
2050	not applicable	not applicable	not applicable	0.08 to 0.55 decrease

Remarks: Operational costs include fuel savings and additional power consumption. Market prices for mineralisers as well as negative costs of alternative raw materials containing fluoride have not been taken into account. Usually no significant investment is required.

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

- The cost of mineralisers can be the key factor. In countries with abundant resources of fluoride, the use of mineralisers is expected to be less cost-intensive
- Grindability of clinker may deteriorate
- Increased coating formation in the sintering zone is possible
- Impact on clinker quality is possible
- Impact on kiln operation and product properties is possible.

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, many long dry or long wet kilns still exist world-wide and are being replaced over time. Compared to long dry and wet kilns, the preheater technique with 3 to 6 cyclone stages improves the calcining efficiency by drying and preheating the raw material using the kiln exhaust gas.

Long wet and long dry kilns without preheater and precalciner have a comparatively high energy demand which may be up to 6,000 MJ/t clinker on average for long wet kilns due to the energy required for water evaporation. A retrofit of a long wet or long dry kiln to a multi-stage preheater or a kiln with precalcining technology may be a feasible but expensive measure for reducing energy demand.

Energy savings depend strongly on the specific energy demand of the existing kiln as well as the number of cyclone stages to be installed. They can be estimated in a range from 900 MJ/t for a long dry kiln and up to 2,800 MJ/t clinker for a long wet kiln compared to a modern preheater system with precalciner and a modern clinker cooler. Due to an extended degree of pre-calcination of the raw meal before entering the kiln inlet, by installing a new preheater, the throughput may be increased up to double the initial long kiln production or even more within the limits of the existing kiln design. In addition, the kiln length may be shortened, reducing radiation losses, the refractory lining and stress on the kiln shell through torsion. However, a large increase in production capacity is likely to require substantial modifications of the cooler, raw mill, cement mills and further installations to handle the higher clinker production capacity. Therefore, the cost of converting a long dry or wet kiln plant to a preheater plant with or without precalciner may be very high. A wet raw material preparation in a so-called "semi-dry" system may still be required depending on the type of raw material (e.g. chalk) used, limiting the energy saving potential significantly.

Impact on energy efficiency

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

CO_2 reduction potential

direct: decrease of 80 to 250 [kg CO_2/t cli]   indirect: decrease of up to 2.5 [kg CO_2/t cli]

Material input

not applicable

The main influencing parameters are

- Initial specific fuel energy demand of the long kiln
- Life cycle of the quarry
- Raw material humidity and 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 cem]
2015	not applicable	not applicable	70 to 100	1.60 to 5.30 decrease
2030	not applicable	not applicable	70 to 100	2.20 to 7.10 decrease
2050	not applicable	not applicable	70 to 100	2.70 to 8.80 decrease

Remarks: The cost estimation for the retrofit cannot be based on a clinker capacity of 2 Mio. t/a (6,000 t/d), because long dry and wet kilns with that capacity do not exist. Therefore, the investment costs given in the table are only indicative for smaller capacities and may be significantly higher depending on local conditions as well as the extent of further plant modifications appropriate or required in conjunction, e.g. modernisation of the grate cooler or the introduction of alternative fuels (Technology Papers Nos. 8 and 10). Depending on the specific situation, the construction of a new kiln line within the existing infrastructure may therefore be more feasible. The mentioned operational costs include only fuel and power savings. The saving potential may 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 costs incur with this measure
- Economics are ruled by fuel, power and CO_2 prices
- Possible capacity increase depends on potential of the throughput increase of single installations (e.g. cooler, raw mill, cement mill).

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

Multi-stage cyclone preheaters are main components for the heat exchange of raw gas and raw meal in the clinker burning process. Typically there are at least 3 and 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 is achieved by geometrical optimisation of the cyclone with nearly constant separation of the kiln meal.

For each hPa of pressure loss reduction, 0.12 to 0.15 kWh per ton clinker from electric energy can be saved depending on the efficiency of the fan. While for most existing kilns of the older type this amounts to savings of 0.6 to 1.5 kWh per ton clinker, two U.S. cement plants' savings of 3 kWh/t cli and 4 kWh/t cli have been reported.

The replacement by low pressure drop cyclones can be economically reasonable when the foundation and tower structure of the existing preheater are usable without rebuilding. In practice, the pressure drop is often balanced by a higher air volume flow increasing the kiln capacity. The costs of such a refurbishment are very site-specific.

Impact on energy efficiency

thermal: not applicable [MJ/t cli]   electric: decrease of 0.6 to 1.5 [kWh/t cli]

CO_2 reduction potential

direct: not applicable [kg CO_2/t cli]   indirect: decrease of up to 1 [kg CO_2/t cli]

Material input

not applicable

The main influencing parameters are

- 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

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	8 to 10	0.05 to 0.11 decrease
2030	not applicable	not applicable	8 to 10	0.05 to 0.12 decrease
2050	not applicable	not applicable	8 to 10	0.06 to 0.14 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a (6,000 t/d) with constant specific costs over time. Investment costs include the replacement of 3 cyclone stages (double string preheater). The impact on operational costs includes the saving of electricity costs.

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

Conditions, barriers, constraints

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

3.4 Technology Paper No. 4: Additional preheater cyclone stage(s)

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

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 the raw material type, geographical location and season. Worldwide it can vary in a range of minimum 2 to 3% by mass and in certain cases exceed 20% by mass. The temperature and therefore the enthalpy in the raw gas strongly depend 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 less common) more than 500°C. The higher the number of existing cyclone stages, the lower the remaining reduction potential per cyclone stage.

The addition of a cyclone stage is only feasible, 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. A high amount of alternative fuels has in some cases led to an increase in the preheater exit gas temperature over time (sometimes by up to 50°C) which may support feasibility. As the upper cyclone stage is normally designed double- string (for better dust separation), at least 2 stages have to be modified. The existing preheater tower structure must allow for an increase in height and therefore structural load. Due to a higher pressure drop a larger exhaust gas fan may be required leading to an increase in the electric power consumption of the kiln. This effect can be limited by using modern low pressure drop cyclones (Technology Paper No 3). Finally, dust cycling in the preheater can be affected (with an effect on power consumption and kiln operation).

The thermal energy demand of a 4-stage cyclone preheater kiln would e.g. decrease by 80 to 90 MJ/t clinker if a 5th stage was added with respect to reduced heat losses. A conversion from 4-stage to 5-stage or 5-stage to 6-stage preheater and no additional power consumption is assumed in the following estimate.

Impact on energy efficiency

thermal: decrease of 80 to 100 [MJ/t cli]   electric: increase possible (see below) [kWh/t cli]

<u>CO_2 reduction potential</u>

direct: decrease of 7 to 9 [kg CO_2/t cli]   indirect: increase possible (see below)
[kg CO_2/t cli]

<u>Material input</u>

not applicable

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

- Raw material moisture content
- Site conditions (free space, material supply, statics of preheater tower)
- CO_2 intensity of the fuels
- Additional power demand due to increased pressure drop, may be limited if low pressure drop cyclones are installed

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	5 to 8	0.15 to 0.19 decrease
2030	not applicable	not applicable	5 to 8	0.20 to 0.25 decrease
2050	not applicable	not applicable	5 to 8	0.25 to 0.31 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 also has to include a new fan and/or preheater tower modification/rebuilding (etc.) as required. **Therefore, costs may increase significantly.** Against this background, additional electricity costs may 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 if exhaust gas temperature is at a low level already
- Technology is only applicable to dry preheater kilns
- Technology is in competition with waste heat recovery.

3.5 Technology Paper No. 5: Increase of 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 to 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. In this way the thermal energy demand 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 cli for a 1,500 t/d plant, but is reduced by about 100 MJ/t cli 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. In this way it is possible to reduce the thermal energy efficiency by more than 400 MJ/t clin 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 larger 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).

Impact on energy efficiency

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

CO_2 reduction potential

direct: decrease of 13 to 18 [kg CO_2/t cli]   indirect: decrease of 1 to 2 [kg CO_2/t cli]

Material input

not applicable

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 demand is related 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 cem]	Investment [Mio €]	Operational [€/t cem]
2015	up to 260	1.4 to 1.7 decrease	not applicable	not applicable
2030	up to 260	1.4 to 1.7 decrease	not applicable	not applicable
2050	up to 260	1.4 to 1.7 decrease	not applicable	not applicable

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a (6,000 tons per day) with 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 the operational costs.

Conditions, barriers, constraints

- High investment costs (financial resources of plant holder)
- Investment costs cannot economically be justified only by CO_2 reduction
- Sufficient raw material deposit
- Legal and environmental conditions.

3.6 Technology Paper No. 6: 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. Primary air is understood as the whole air which is led through the burner is (e.g. transport, swirl, axial air, etc.). Secondary and tertiary combustion air is preheated in the clinker cooler to 600 to 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 in fuel energy demand.

In some regions of the world, mono-channel burners are still also 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 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 to 25% (often the burners are in direct compound operation with the coal mill), modern multi-channel burners are operated with around 8 to 12%. Depending on the secondary air temperature, reduction of the primary air ratio by 5 to 10% will lead to a fuel energy saving of 50 to 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 alternative fuels. These effects are not considered further in this paper.

Impact on energy efficiency

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

electric: no significant impact [kWh/t cli]

CO_2 reduction potential

direct: decrease of 2.2 to 6.5 [kg CO_2/t cli]

indirect: no change [kg CO_2 /t cli]

Material input

not applicable

The main influencing parameters are

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

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicabe	not applicabe	0.45 to 0.6	0.04 to 0.27 decrease
2030	not applicabe	not applicabe	0.45 to 0.6	0.06 to 0.36 decrease
2050	not applicabe	not applicabe	0.45 to 0.6	0.08 to 0.45 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, constraints

- Investment cost
- Prices trends for primary and alternative fuels will determine this measure.

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 in the energy efficiency, production capacity or substitution of fossil fuels by low calorific value or (alternative) fuels. Experience with oxygen enrichment showed a reduction of specific energy demand by up to 5%.In this 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. Oxygen enrichment is limited by increasing damage of the kiln refractory and theoretically higher NO_X emissions due to the potential increase in thermal NO_X formation in the sintering zone. Some research projects in the field of oxygen enrichment have been conducted in the past years but the relation between the theoretical increase of NO_x formation and the use of oxygen enrichment technology was not conclusive. In practice, the application of the oxygen enrichment contains potential for further optimisation with respect to NO_x-emission reduction. Due to reduced secondary air flow the heat recuperation in the clinker cooler might also be affected for example by a higher secondary air temperature. The oxygen enrichment technology is established in some cement plants in order to improve production capacity in periods of high market demand. An increase of 25 to 50% (short term experiments) kiln capacity by oxygen enrichment to 30 to 35 volume% 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 volume% 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 of 100 to 175 [MJ/t cli]   electric: increase of 10 to 35 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 9 to 15 [kg CO_2/t cli]   indirect: increase of 5 to 18 [kg CO_2/t cli]

Material input

not applicable

The main influencing parameters are

- Location of the oxygen supply system (on-site or off-site)
- Electric energy demand of the air separation unit (oxygen generation technology)
- 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 cem]	Investment [Mio €]	Operational [€/t cem]
2015	5 to 10	increase of 0.4 to 1.9	5 to 10	increase of 0.4 to 1.9
2030	5 to 10	decrease of 0.5 to 2.1	5 to 10	decrease of 0.5 to 2.1
2050	5 to 10	decrease of 0.5 to 2.4	5 to 10	decrease of 0.5 to 2.4

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, with 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. Increased kiln capacity or increased alternative fuel consumption have not been taken into account as separate technology papers for these topics exist. Depreciation, interest and inflation are not included in operational costs. A commercial agreement between gas producers and the cement plant to supply oxygen "over the fence" can also be negotiated. In these cases, the oxygen supplier erects, owns and operates the oxygen plant against a monthly fee. The cement plant reduces CAPEX but increases OPEX. Since OPEX closely depends on the terms of the commercial agreement, these were not included in the assessment.

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

- Integration of energy flows between the additional air separation unit and the cement plant
- Further development in oxygen supply technology influences 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: Efficient clinker cooler technology

In cement production the energy of the hot clinker leaving the cement kiln is transferred in the clinker cooler where 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 80°C above ambient temperature). Grate coolers use more cooling air and therefore create a cooler exhaust air which is emitted and 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

Principally, planetary or rotary coolers can be replaced by grate coolers. Usually, this is only economically viable if the retrofit is linked to a change to precalciner technology and a significant capacity increase. Modern reciprocating grate coolers (so-called 3rd generation) can be operated against 2nd generation or travelling grate coolers with extended lifetime and less heat losses. Grate coolers (and rotary coolers) can provide the precalciner with preheated tertiary air. Existing (2nd generation) grate coolers with a typical efficiency of 50 to 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. With increased thermal efficiency of the kiln system, clinker coolers are required to operate with reduced volumes of secondary and tertiary air and with higher recuperation efficiency.

Several improvements in clinker cooler technology are under development with regard to better air distribution for reduced cooling air requirement, an effective conveying system for better transport of clinker and mechanical stability of the cooler, optimum under-grate pressure and heat shields. Compared to planetary or rotary coolers, heat recovery with grate coolers requires additional electrical power of approximately 3 to 6 kWh/t clinker. Modern reciprocating coolers can have a high degree of heat recuperation efficiency up to 75 to 80%. The total heat loss of latest generation clinker coolers is less than 0.42 MJ/kg clinker. Thermal energy saving in the kiln with the modern grate coolers is estimated to be up to 8%.

The cost for the conversion from a planetary cooler to an efficient reciprocating grate cooler of the newest generation with a capacity of 6.000 tons per day is estimated at 15 to 20 Mio. €. These costs can vary widely due to the site-specific conditions (new exhaust air fan and cooler filter, foundations and other construction costs, shortening of the kiln). The optimisation of clinker coolers (e.g. replacement of cooler plates, installation of a fixed grate section at the cooler inlet) is also an opportunity for some existing kilns, but efficiency improvement

potentials are smaller. The retrofit of an old grate cooler requires an investment of 1 to 3 Mio. €.

Impact on energy efficiency

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

CO_2 reduction potential

direct: decrease of 22 to 26 [kgCO$_2$/t cli]   indirect: increase of 2 to 4 [kgCO$_2$/t cli]

Material input

not applicable

The main influencing parameters are

- Throughput of clinker
- Requirement of tertiary air for modern precalciner (e.g. combined with capacity increase)
- Degree of efficiency of existing cooler type
- Requirement of higher secondary air temperature, e.g. to improve secondary fuel combustion
- Amount of false air
- Temperature at clinker discharge
- Fuel mix.

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	1 to 3 or 15 to 20 (complete replacement)	0 to 0.5 decrease
2030	not applicable	not applicable	1 to 3 or 15 to 20 (complete replacement)	0 to 0.5 decrease
2050	not applicable	not applicable	1 to 3 or 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 the 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 alternative fuel use can be increased in the kiln firing
- Investment costs are high for replacement of rotary or planetary cooler.

3.9 Technology Paper No. 9: Waste heat recovery: Steam

Waste heat from cement kilns is usually used for the 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 the cooler exhaust air. Principally this heat can be used for the drying of other materials like slag or alternative fuels or for steam or electric power production. As raw material drying is a key requirement for a cement plant, heat recovery has limited application for plants with higher raw material moisture content. Often, the 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 steam turbine is the technology best known from power plants. While in modern power plants with a water steam cycle ("Steam Rankine Cycle") the electric efficiency amounts to 46%, the relatively low temperature level of the waste heat in cement plants (200 to 400 °C) limits the efficiency to a maximum of 20 to 25%.

The Steam Rankine Cycle describes the process by which steam-operated heat engines generate power. Usually water is used as the fluid of choice due to its good properties, such as its unreactive chemistry, low cost, and its well-studied thermodynamic properties. The steam cycle is well proven and heat exchangers can be placed directly in flue gas channels. The disadvantage of the steam cycle is that at decreasing temperature levels of the heat source (low operating pressures) the dimension of the evaporators rises (increase in investment cost). The application of the steam technology for use in cement plants was developed and first implemented in Japan due to high energy costs and relatively low capital costs. The technology has spread from Japan to other continents. It is used predominantly in China where it has become a kind of 'standard', as a way to respond to issues related to the power supply to industry as part of a national strategy, in India and in other Asian countries. However, in many other regions with unstable power supplies conventional stand-alone power generation solutions are still preferred to WHR. Some interest is can be detected in Europe, but high project costs are the main barrier.

Depending 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. In total, between 8 and 22 kWh/t clinker or up to 16% of the power consumption of a cement plant can be produced by using these technologies without changes to the kiln operation. If higher power production is needed, WHR is in certain competition with the energy efficiency of the clinker production, but in the end both techniques aim at the minimisation of unused waste heat.

If the 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 a modification of the kiln system (e.g. less cyclone stages or bypassing upper stage(s)). Figures of up to 45 kWh/t clinker have been reported. Depending on local conditions this can be an attractive option.

Impact on energy efficiency

thermal: 0 [MJ/t cli]   electric: decrease of 8 to 22 [kWh/t cli]

It is assumed that no additional fuel is used to produce more electricity than is possible from waste heat and that the kiln operation has not been modified. The absolute power consumption of the clinker production will slightly increase (demand of boiler and turbine), but the net power consumption will decrease.

CO_2 reduction potential

direct: 0 [kg CO_2/t cli]   indirect: decrease of 4 to 11 [kg CO_2/t cli]

Material input

not applicable

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
- 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	0.5 to 1.4 decrease	15 to 25	0.5 to 1.4 decrease
2030	15 to 25	0.6 to 1.6 decrease	15 to 25	0.6 to 1.6 decrease
2050	15 to 25	0.7 to 1.9 decrease	15 to 25	0.7 to 1.9 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a and a boiler/steam turbine cycle including construction, with constant specific costs over time. Operating costs include power saving, personnel and maintenance costs.

Conditions, barriers, constraints

- Availability of excess heat: raw material humidity is the key factor
- Investment costs 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 by co-firing additional fuels
- Economics can be improved by firing alternative fuels
- Minimum kiln capacity is needed
- Cost of additional manpower.

3.10   Technology Paper No. 10: Waste heat recovery: ORC

Waste heat from cement kilns is usually used for the drying of raw materials like limestone, clay or marl. Depending on the moisture content 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 the drying of other materials such as slag or alternative fuels or for steam or electric power production. As raw material drying is key for a cement plant, heat recovery has a limited application for plants with higher raw material moisture content. Often, the drying of other materials is recommendable and comparatively efficient as it is process integrated. The Organic Rankine Cycle (ORC) process is also suitable for waste heat recovery from small and medium sized cement plants (1,500 – 3,000 tpd) with higher raw material moisture.

Power production from waste heat requires a heat recovery boiler and a turbine system. Power generation can be based on the Organic Rankine Cycle process. While in modern power plants with water steam cycles the electric efficiency amounts to 45 to 46%, the relatively low temperature level of the waste heat in cement plants (200 to 400 °C) limits the efficiency to a maximum of 20 to 25%. The Organic Rankine Cycle technology is a modified version of the steam cycle. Its efficiency is normally less than 15%.

The Rankine Cycle does not restrict the working fluid in its definition. In the Organic Rankine Cycle organic fluids such as n-pentane or toluene are used instead of water and steam. Due to the lower boiling point of these substances, low-temperature heat sources, such as cooler exit gas, which typically operates at around 150 to 350 °C, can be used. Therefore, electric power can be produced at a temperature level at which (water) steam turbines cannot work efficiently. As -compared to (water) steam cycles superheating of the gas does not bring an increase in efficiency, ORC systems do not require super-heaters. Therefore, the equipment is overall less expensive. For safety reasons it is required that a thermo-oil circuit between the heat-source and the working fluid is used, making it a two-stage heat transfer process. Depending on the temperature, the efficiency of the ORC system ranges between 10 and 20%. The first ORC installations were built in a German cement plant in 1999 using heat from cooler waste air. Since then several ORC boilers have been implemented in cement plants on different continents.

In total between 10 and 20 kWh/t cli can usually be produced by using ORC technologies.

Impact on energy efficiency

thermal: 0 [MJ/t cli]   electric: decrease of 10 to 20 [kWh/t cli]

It is assumed that no additional fuel is used to produce more electricity than is possible from waste heat and that the kiln operation has not been modified. The absolute power consumption of the clinker production will slightly increase (demand of boiler and turbine), but the net power consumption will decrease.

CO_2 reduction potential

direct: 0 [kg CO_2/t cli]   indirect: decrease of 5 to 10 [kg CO_2/t cli]

Material input

not applicable

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
- 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
- Temperature level of waste heat available for heat recovery
- 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 cem]
2015	15 to 25	0.5 to 1.4 decrease	15 to 25	0.5 to 1.4 decrease
2030	15 to 25	0.6 to 1.6 decrease	15 to 25	0.6 to 1.6 decrease
2050	15 to 25	0.7 to 1.9 decrease	15 to 25	0.7 to 1.9 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, and a boiler/steam turbine cycle including construction, with constant specific costs over time. Operating costs include power saving, personnel and maintenance costs.

Conditions, barriers, constraints

- Availability of excess heat: raw material humidity is the key factor
- Investment costs 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
- Economics can be improved by firing alternative fuels
- Minimum kiln capacity is needed
- Cost of additional manpower.

3.11 Technology Paper No. 11: Waste heat recovery: Kalina Cycle

Waste heat from cement kilns is usually used for the drying of raw materials like limestone, clay or marl. Depending on the moisture 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 the drying of other materials like slag or alternative 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, the drying of other materials is recommendable and comparatively efficient as it is process integrated. The Kalina process for waste heat recovery is designed to achieve the highest efficiencies in the low-temperature range.

Power production requires a heat recovery boiler and a turbine system. Power generation can be based on the Kalina process. While in modern power plants with a water steam cycle the electric efficiency amounts to 45 to 46%, the relatively low temperature level of the waste heat in cement plants (200 to 400 °C) limits the efficiency to a maximum of 20 to 25%. The installation cost is higher due to the corrosiveness of NH_3. Kalina technology uses NH_3 as a cycling media which evaporates at lower temperatures and can therefore produce electric power at a temperature level at which steam turbines cannott work efficiently. The electrical efficiency of these installations is usually between 20 and 25%.

The Kalina cycle is another variation of the Rankine cycle and has been developed for heat recovery at low temperature sources. It uses a blended solution of two fluids with different boiling points for its working fluid. Since the solution boils over a range of temperature as in distillation, more of the heat can be extracted from the source than with (one) pure working fluid. The same applies on the exhaust (condensing) side of the cycle. This provides a higher efficiency at lower temperatures with less complexity. Water and ammonia is the most widely used fluid combination. With a designed ratio between these two components of the working fluid, its boiling point can be adjusted to the heat input temperature. The evaporation at rising temperatures helps to reduce exergy loss. This is especially important for low temperature/exergy systems.

The Kalina cycle is used in industrial waste heat processes, geo-thermal energy recovery, and solar energy because of its adaptability to the temperature level of the particular heat source. The Kalina process is promising, but currently worldwide only a few systems are in operation. In the cement industry, the Kalina process is known to be already implemented in Pakistan and the United Arab Emirates.

In total between 10 and 22 kWh/t cli can be produced by using this technology without changes to the kiln operation. If higher power production is needed, WHR is in certain competition with the energy efficiency of clinker production, but in the end both techniques are aim at the minimisation of unused waste heat.

Impact on energy efficiency

thermal: 0 [MJ/t cli]   electric: decrease of 10 to 22 [kWh/t cli]

It is assumed that no additional fuel is used to produce more electricity than is possible from waste heat and that the kiln operation has not been modified. The absolute power consumption of clinker production will slightly increase (demand of boiler and turbine), but the net power consumption will decrease.

CO_2 reduction potential

direct: 0 [kg CO_2/t cli]   indirect: decrease of 5 to 11 [kg CO_2/t cli]

Material input

not applicable

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
- Temperature level of waste heat available for heat recovery

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli or cem]	Investment [Mio €]	Operational [€/t cli]
2015	15 to 25	0.5 to 1.4 decrease	15 to 25	0.5 to 1.4 decrease
2030	15 to 25	0.6 to 1.6 decrease	15 to 25	0.6 to 1.6 decrease
2050	15 to 25	0.7 to 1.9 decrease	15 to 25	0.7 to 1.9 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a and a boiler/steam turbine cycle including construction, with constant specific costs over time. Operating costs include power saving, personnel and maintenance costs.

Conditions, barriers, constraints

- Availability of excess heat: raw material humidity is the key factor
- Investment costs 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 by co-firing additional fuels
- Economics can be improved by firing alternative fuels
- Minimum kiln capacity is needed
- Cost of additional manpower.

3.12 Technology Paper No. 12: Alternative de-carbonated raw materials for clinker production

The utilisation of alternative calcium containing raw materials which are already de-carbonated offers a chance to reduce CO_2 emissions. This is a twofold chance since process-related CO_2 emissions from the de-carbonation of the raw materials as well as CO_2 emissions from the related fuel consumption can be reduced.

Blast furnace slag, lignite ash, concrete crusher sand, carbide sludge, aerated concrete meal or lime residues from the sugar industry are examples of such de-carbonated 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 and added to the composition of cement clinker. An excess amount of silica, alumina, magnesia or sulphur may therefore hinder a large-scale utilisation of alternative de-carbonated raw materials, and the content of VOC or trace elements and a variable composition may cause a further restriction in some cases. Furthermore the availability of such de-carbonated raw materials is often limited. Further preparation steps, e.g. in the case of concrete crusher sand, may improve the quality of the material but also increase the costs and the environmental efforts for the material supply. The following ranges are determined on one hand by the fact that the local situation may allow no or only a very limited use of alternative de-carbonated raw materials. On the other hand, the use of granulated blast furnace slag (GBFS) may be realistic up to the amount of 15% of the raw meal in a few cases. The utilisation of an even higher amount is in principle possible but seems to be unrealistic in any case due to the decreasing availability of GBFS and its rising costs. Moreover, additional effort for the grinding of these materials is needed because of their structure, requiring a higher electrical energy demand.

Impact on energy efficiency

thermal: decrease of 100 to 400 [MJ/t cli]   electric: increase of 0 to 3 [kWh/t cli]

CO_2 reduction potential

direct: decrease of up to 100 [kg CO_2/t cli]   indirect: increase of 0 to 2 [kgCO_2/t cli]

(for a 10 to 15% replacement of raw materials by GBFS)

Material input

GBFS   0.2 to 0.3 [t/t cli]

The main influencing parameters are

These figures have to be regarded as possible site-specific reduction potentials, but not as a 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
- Local availability and cost of decarbonated raw materials

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 even be negative, especially if waste materials are used and the cement company is paid for using them. Additional costs, which have not been taken into account in the cost estimation, may be incurred by the impact of wear and tear on the system caused by raw meal.

Conditions, barriers, constraints

- The potential of 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 only at very few sites, and additionally the use of such materials is in general limited close to their source
- The amount of alternative materials is limited and different ways of their utilisation may additionally restrict the available amount or may make it more expensive; granulated blastfurnace slag is, e.g. important as a 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 the 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.

3.13 Technology Paper No. 13: Fuel switching (coal/petcoke →oil/gas/pure biomass)

Fuel switching is one of the most discussed CO_2 reduction measures apart from in the cement industry. Usually, it refers to the switch from coal to oil or gas, but increasingly biomass is also coming into the focus. The CO_2 reduction potential of switching from hard coal to heavy fuel oil is about 16%, whereas the switch to natural gas leads to a 40% reduction related to the energy content of the fuels and their energy-specific CO_2 emission factor. The use of lignite leads to even higher relative CO_2 emissions than hard coal.

Based on the GNR data for the year 2014, the use of alternative fuels on a global level was 16% in relation to the total fuel energy demand for cement manufacturing. Almost 6% was covered by biomass and the remaining 84% was provided by fossil fuel, mainly coal and petcoke. The variations on a global level in the different regions were significant. Gas and oil play a role in countries where these fuels are produced and local prices are thus comparatively low. Technically, cement kilns can be operated with 100% oil or gas, but in many regions this is not economically viable.

As the fuel-related CO_2 emissions are about one third of the total emissions (306 of 842 kg CO_2 per tonne of clinker), the CO_2 reduction potential is in principle significant if pure biomass use is assumed. If pure biomass is used in significant amount a further decrease in CO_2 can be achieved.

Pure biomass fuels used in the cement industry today are biomass wastes, mainly waste wood, rise husk, sawdust, sewage sludge and animal meal. In principle it is also possible to use any type of organic material as a biomass fuel, allowing the use of liquid biomass and biomass products, e.g. palm oil, corn, wood products or certain grass types (e.g. miscanthus or other fast-growing species). The use of biomass products as feedstock relates to questions on sustainability and greenhouse gas emissions from agriculture, forestry and land use. 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 this will probably enable 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. Biomass share of fuels is expected not to exceed 30% or 40% (corresponding to a maximum of 90 or 120 kg CO_2 from biomass). In practice, the impacts on thermal and electric energy demands are similar to those of alternative fuels (see Technology Paper No. 14).

The following figures refer to the substitution of hard coal with oil or gas.

<u>Impact on energy efficiency</u>

thermal: decrease of 200 [MJ/t cli]   electric: no significant change [kWh/t cli]

           increase of 100 [MJ/t cli]

<u>CO_2 reduction potential</u>

direct: decrease of 40 to 60 [kg CO_2/t cli]   indirect: no significant change [kg CO_2/t cli]

<u>Material input</u>

Hard coal   decrease of 115 [kg/t cli]

Fuel oil or   increase of 70 [kg/t cli]

Natural gas   increase of 84 [Nm^3]

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

- Technical equipment of the plantFuel costs
- Fuel type (C / H ratio, calorific value)
- CO_2 intensity of fuel mix
- Maximum possible substitution rate and sustainability in case of biomass fuel use

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not available	not available	5 to 15	8 to 16 increase
2030	not available	not available	5 to 15	8 to 16 increase
2050	not available	not available	5 to 15	8 to 16 increase

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time and no inflation. The operational cost is expressed as additional costs and includes only fuel costs as these are the main economic driver besides investment costs. The use of oil and gas is related to very high prices with significant regional differences. The development of biomass prices over time has not been predicted because it depends on many factors such as energy and CO_2 policies, availability on a regional level, etc.

Conditions, barriers, constraints

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

3.14 Technology Paper No. 14: Alternative fuels (including biomass) replacing conventional fossil fuels

The CO_2 reduction potential of alternative fuels is based on two effects: First, many waste fuels contain certain biomass content which is calculated as CO_2 neutral. Second, most fossil waste fuels have lower CO_2 emission factors related to the calorific value than coal or pet-coke. Pure biomass fuels used in the cement industry today are mainly waste wood, rice husk, saw dust, sewage sludge, and animal meal. Besides these fuels, many other organic waste materials are used as fuels in the cement industry globally at a lower level. Wastes containing biomass are mainly pre-treated industrial and domestic wastes (containing certain parts of organic fibres and textiles, paper, etc.) as well as waste tyres, which contain between 20 and 35% of natural rubber.

In principle, cement kilns can burn up to 100% of waste or biomass 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 to 18 GJ/t). For the main firing of the cement kiln typically an average calorific value of at least 20 to 22 GJ/t for the fuel mix is required. In the precalciner of modern cement kilns, in which up to 60% of the fuel input is realised, the lower process temperature also allows the use of low calorific fuels. Therefore, precalciner kilns are able to burn at least 60% of low calorific (alternative and/or biomass) fuels. A lower calorific value as well as high-chlorine content (requiring a chlorine bypass system) will increase the specific fuel energy demand per tonne of clinker. Therefore, it is possible that although the use of these fuels leads to higher energy demand, CO_2 emissions are reduced nevertheless.

As the operation of cement kilns running at very high substitution rates differs significantly from the operation with pure fossil fuels, the penetration of technical operational experience within companies or between different groups is also a major criterion for the use of such fuels on a global level. Experience shows that increasing of the alternative fuel substitution rate may increase specific fuel energy demand per tonne of clinker.

Employing fuels with high concentrations of chlorine and sulphur in addition to the contribution of raw material may cause operational problems in the kiln system at very high substitution rates. This is attributed to the fact that circulating sulfur systems, together with chlorine and alkali circulating systems, may lead to increased coating formation in the kiln inlet, gas riser duct and lower cyclone stages, and also formation of rings in the rotary kiln. Any additional number of kiln stops increases the specific energy demand. To improve the process procedure, build-ups must be cleaned off manually or automatically. Another measure is the installation of a bypass in the kiln inlet in order to reduce the chlorine and sulfur content in the kiln atmosphere.

The following figures refer to an increase in the substitution rate of alternative fuels of up to 65%. This could be related to an increase of the specific energy demand up to 8,5%.

Impact on energy efficiency

thermal: increase of 200 to 300 [MJ/t cli]   electric: increase of 2 to 4 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 30 to 50 [kg CO2/t cli]   indirect: increase of 1 to 2 [kg CO_2/t cli]

Material input

Alternative fuel mix including 30% to 40% biomass   increase of 0.12 [t/t cli]
(RDF, plastics, waste tyres, sewage sludge, etc.)

Fossil fuel (coal, petcoke, natural gas etc.)   decrease of 0.06 [t/t cli]

The main influencing parameters are

- Kiln type, technical equipment of the plant (silos, dosing station)
- Fuel properties of alternative fuels (including biomass)
- Biomass content of wastes
- Availability of biomass-containing wastes and/or biogenic material (competition with other industry sectors such as power plants, steel industry)
- CO_2 intensity of fuel mix
- Limitation on substitution rate by employing various types of alternative fuels, for example, used tyres up to 25%
- Thermal energy required for the drying of alternative fuels in the process

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cli]
2015	not available	not available	5 to 15	2 to 2,5 decrease
2030	not available	not available	5 to 15	1 to 5 decrease
2050	not available	not available	5 to 15	0 to 2 increase

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time and no inflation. Operational costs are expressed as savings and include only fuel cost savings as these are the main economic driver besides investment costs. It is assumed that waste fuel prices will amount to about 30% of coal prices in 2030 and 70% in 2050.

Conditions, barriers, constraints

- Availability, quality and price of waste fuels will be the key factors
- Waste fuels 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 be present in many regions
- Higher investment and operating costs of waste pre-processing facility
- Negative impact on kiln operation (lifetime of refractory materials, cyclone blockages, etc.).

3.15   Technology Paper No. 15: Pre-treatment of alternative fuel (grinding, drying)

For the use of alternative fuels the fuel properties have to stay within a certain range. For example, for the main burner, the net calorific value of the fuel mix should be above approximately 20 to 22 GJ/t and for use in the calciner the net calorific value should exceed approximatly 13 GJ/t. The fuel has to be fine enough so that it burns completely in the gas phase, especially when feeding to the main burner. Alternatively, fuels can also be fed to the kiln inlet.

Some alternative materials have high moisture content and their net calorific value is therefore generally low (e.g. mechanically dried sewage sludge: < 5 GJ/t, pulp waste: 6 to 12 GJ/t, municipal solid wastes: 8 to 10 GJ/t). These wastes can be dried thermally in the cement plant by using dryers and waste heat from the kiln system. If fractions of the fuel are too coarse, mills can be operated to increase the fineness. Some mills are designed for the combined comminution and thermal drying of fuels. By raising the net calorific value and/or the fineness, alternative fuels can be made suitable for the main firing system or the substitution rate can be increased. First installations of dryers and mills for alternative fuels have been reported in the cement industry, but the technology is still emerging. Belt driers, drum driers and flash dryers are used for drying sewage sludge or RDF with clinker cooler vent air. Cutting mills and chain mills are used for the comminution of RDF. The installation and operation of dryers and mills require CAPEX and OPEX that are amortised by fuel cost reduction compared to conventional fuels.

A positive effect of the drying technology is that moisture can be removed before the fuels are burnt in the kiln, so the kiln exhaust gas volume is reduced, resulting in a lower energy demand for the main ventilation fan. If the kiln fan operates at its full capacity, installing a dryer for the fuel increases the kiln clinker capacity. This positive effect only counts when the moist waste gas of the drying process is not fed back into the kiln system. In other cases additional investments in additional filters or combustion devices have to be installed to clean the dryer waste gas. Additional power consumption for the operation of mills and the dryer has to be taken into account.

Impact on energy efficiency

thermal: decrease of 0 to 160 [MJ/t cli]   electric: increase of 1 to 3 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 0 to 14 [kg CO_2/t cli]   indirect: increase of 0.6 to 1.6 [kg CO_2/t cli]

Material input

Alternative fuel: Coarse RDF   grinding of 0,02* [t/t cli]

or

Alternative fuel: Sewage sludge, 80% water content   pre-drying of 0,05 [t/t cli]

The main influencing parameters are

- CO_2 footprint of the power mix
- Availability of alternative fuels (sewage sludge, refuse-derived fuel, industrial sludges)
- Fuel properties (water content, fineness, homogeneity)
- Availability of thermal energy for biomass or alternative fuels drying process
- Kiln type (with/without precalciner, long/short kiln)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	8 to 20	decrease 0.1 to increase 0.1	8 to 20	decrease 0.1 to increase 0.1
2030	8 to 20	decrease 0.2 to increase 0.1	8 to 20	decrease 0.2 to increase 0.1
2050	8 to 20	decrease 0.2 to increase 0.1	8 to 20	decrease 0.2 to increase 0.1

Remarks:

- Operational costs depend on the fuel feedstock and related cost structures
- Fuel properties and unwanted components in waste fuels may cause wear of material and can increase operational costs significantly
- *The scenario for alternative fuel grinding refers to higher rates of subsitution by alterntative fuels and reflects the increased electrical power use. The CO_2 reduction potential of fuel substitution is described in Technology Paper No. 14.

Conditions, barriers, constraints

- Availability of waste heat
- Environmental regulations
- Disruptive materials in the fuel, i.e. pieces of metal.

3.16 Technology Paper No. 16: Gasification or pre-combustion of alternative fuels

In some locations the availability of adequate waste materials or biomass, or other plant-specific boundary conditions (e.g. composition of the raw material in terms of sulphur) limit the maximum achievable alternative fuel substitution rate which can be used without creating process instability. Pre-combustion or gasification processes allow for more flexibility on fuel quality with regard to homogeneity, calorific value, moisture content, hazardous contents or sizes. Whereas pre-combustion chambers are operated at excess oxygen, in gasification/pyrolysis processes the fuel is burned in an oxygen-poor atmosphere to generate a lean gas which contains CO, H_2 and CH_4 and therefore offers a certain heating value.

Typical pre-combustion chambers equipped with a burner to support the calciner firing are widely-used. Ignition is enhanced as fuel is combusted in high oxygen atmospheres (21 vol.%) and at higher temperatures (up to 1200°C). Additional retention time (up to 10 seconds) allows an enhanced burn-out of alternative fuels. Advanced systems even increase the retention time (up to 45 min) or use stepped combustion to properly combust even different coarse waste materials. The mineral fraction and ashes of the waste fuels become part of the product. Those advanced solutions are commercially available but rarely applied.

Using gasification processes a lean gas is provided to the calciner or kiln inlet area, where it is completely oxidized. In this way the energy input can be homogenized which leads to stabilisation of the clinker burning process. Due to the more efficient pyrolysis with regard to the process-integrated drying of the alternative fuels, the gasification technology can counteract the increasing impact of alternative fuel use on the specific energy demand. The gasification can facilitate the use of fuels with calorific values of e.g. 4.5 to 6.0 MJ/kg without pre-treatment, as long as the fuels are appropriate for handling (low fine fraction) and dosing (not sticky) and metallic particles/fractions are removed. Residues from the pyrolysis can either be disposed to disburden certain element cycles or transferred to the raw material preparation/kiln inlet. Recent applications have shown problems with the discharge of hot ashes or unburned particles (e.g. metal wires) or clogging of lean gas tubes to the calciner, which again puts requirements on the fuel quality. In certain applications the introduction of lean gas can generate locally reducing atmospheres leading to additional NO_x reduction. For smaller applications the fuel can be gasified in a fixed bed reactor and above 10 MW in a fluidized bed reactor. Such systems are commercially available but still not widely used. Research projects are also focusing on new gasification routes like plasma gasification. In this approach an electric arc is generated which ignites the alternative fuels. In this way the fuel use could be optimised, but high power demand is related to the generation of the plasma. In any case the resulting lean gas at temperature levels of 800 to 1000°C offers a LHV level of 4 to 6 MJ/m^3 using air as a media and up to 14 MJ/m^3 using steam. The application of plasma gasification in the cement industry has been investigated but is still not proven in demo-scale.

Impact on energy efficiency

thermal: increase up to 100 [MJ/t cli]   electric: increase up to 2 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 40 to 45 [kg CO_2/t cli]   indirect: increase up to 1 [kg CO_2/t cli]

Material input

alternative fuels   0.1 to 0.15 [t/t cli]

The main influencing parameters are

- CO_2 reduction potential mainly depends on the substitution rate of alternative fuels and their biogenic fraction
- Technology used: In the case of plasma gasification higher thermal reduction is expected at higher electrical demand
- CO_2 footprint of the power mix

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	5 to 15	1.8 to 2.1 decrease	5 to 15	1.8 to 2.1 decrease
2030	5 to 15	1.1 to 1.3 decrease	5 to 15	1.1 to 1.3 decrease
2050	5 to 15	0.5 to 1.1 increase	5 to 15	0.5 to 1.1 increase

Remarks: The cost estimation is based on a designed clinker capacity of 2 Mio. t/a. Additional costs for fuel storage are excluded. Pre-combustion chambers are estimated on a lower investment level than gasifiers. Calculations of operational costs include the increase of alternative fuel use by 50 to 60%. The cost estimation does not include losses of revenues during kiln stops caused by the direct use of alternative fuels.

Conditions, barriers, constraints

-   Direct combustion of fuels is more economic. Today gasification is only an option for difficult combustible fuels and is aimed at the stabilisation of the clinker burning process
-   Prices for alternative fuels are expected to rise at steeper rates than fossil fuels, which strongly influences the forcast of operational costs in 2030 and 2050
-   Plasma gasification could become a solution for the transition to flexible regenerative power, but is still not proven in demo-scale
-   Even higher CO_2 reduction is possible when using regenerative power
-   Suitable for locations where the availability of appropriate fuels is limited.

3.17 Technology Paper No. 17: Hydrothermal Carbonisation (HTC) and Torrefaction

Hydrothermal Carbonisation (HTC) is a process of carbonisation in aqueous solution, under pressure and increased temperature at about 1.8 MPa and 200°C. It was described in 1913 by Friedrich Bergius and has similarity to the process of geological lignite formation. Nearly any type of biomass can be used as a feedstock, which allows for the use of wet and waste biomass materials, e.g. sewage sludge. After a few hours the HTC char product contains 70% to 90% of the carbon, has similarity to lignite and net calorific values often between 12 and 24 MJ/kg depending on the feedstock. About 25% of the energy contained in the biomass feedstock is required for starting the exothermal HTC process and for its electrical energy demand (4400 MJ thermal and 300 kWh electrical energy per tonne HTC char). The produced char is hydrophobic. Mechanical drying down to 20% residual moisture is therefore very efficient. Thus, the process can offer substantial energy savings compared to traditional thermal drying of biomass fuels.

The increased energy density of the HTC product allows for further substitution of fossil fuels in a cement plant by waste-derived biomass fuel. Its inorganic content contributes to the composition of clinker. Currently, the costs of the HTC process limit its economic application to waste fuel sources with significant negative costs, e.g. a gate fee of 50 €/t waste in order to produce HTC char at a cost of 0 €/t. Current research reports are being followed by pilot and industrial scale demonstrations planned in 2016. Further development of the HTC technology and economies of scale may decrease related costs in the future. The potential use of HTC char from sewage sludge as an alternative fuel in the cement industry at a relevant scale will likely require the extraction of phosphorus through a separate acid leaching process and/or the reduction of metal concentrations in the feedstock. At the same time, a potential increase in the chloride or sulphate content of the HTC char might limit its application in the clinker production process.

Torrefaction is a process of dry pyrolysis which can change the fuel properties of solid biomass. It is mainly applied to relatively dry solid biomass such as wood products for better grindability, the decrease of the transport weight on long distances and the production of durable pellets. About 10% of the energy contained in the biomass is used for its torrefaction and drying to about 5% to 10% residual moisture. Correspondingly, the net calorific value of the product is increased to about 20 MJ/kg. Standardisation of torrified fuel products is ongoing. They may allow the increase of biomass use in industrial plants at the expense of about 14 kg indirect CO_2/GJ in their production and supply chain. To a large extent the price depends on the cost of the biomass feedstock and is therefore estimated at about 10 €/GJ, similar to unprocessed wood pellets.

Impact on energy efficiency

thermal: increase of 176 [MJ/t cli]*   electric: increase of 12 [kWh/t cli]*

CO$_2$ reduction potential

direct: decrease of 65 [kg CO$_2$/t cli]   indirect: increase of 6.1 to 9.8 [kg CO$_2$/t cli]*

Material input

biomass wastes, e.g. sewage sludge   increase of 0.18 to 0.28 [t/t cli]

fossil fuel demand, e.g. lignite   decrease of 0.03 [t/t cli]

The main influencing parameters are

- Availability of sustainable biomass feedstock
- Biomass content of fuel mix in the cement plant, here assumed 20% increase
- * Energy demand of HTC or torrefaction process
- Clinker and cement production with unchanged energy efficiency

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not available	not available	included in operational cost **	increase of 5.4 to 10.3
2030	not available	not available	included in operational cost **	increase of 4.0 to 6.6
2050	not available	not available	included in operational cost **	increase of 2.7 to 4.7

Remarks:

- ** The cost estimation is performed for the HTC process by transforming indicated gate fees (e.g. 50 €/t sewage sludge) to operational costs for an existing cement plant (retrofit). The HTC plant investment is thereby included in the operational costs.
- Extraction and recovery of phosphorous is estimated to add 10% to indicated costs.

- Fuel products from the torrefaction of solid biomass show a very similar estimated impact on operational costs

Conditions, barriers, constraints

- Sewage sludge as a biogenic waste feedstock results in HTC char with low net calorific values of about 12 to 16 MJ/kg giving limited potential for fossil fuel substitution at the kiln main burner and high energy-specific costs
- The current overall cost of a HTC plant yields an estimated very high specific abatement cost of more than 100 €/t CO_2 avoided in a case with no gate fee for the biomass feedstock (5.4 to 10 €/t cem for a net decrease of 44 kg CO_2/t cem)
- Use of solid biomass products like wood as feedstock for HTC or torrefaction should relate to questions on sustainability and greenhouse gas emissions from forestry and land use (FOLU)
- A global market for sewage sludge up to 170 Mt/year means less than 38 Mt/year HTC char as a theoretic maximum.

3.18 Technology Paper No. 18: 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 the key for a smooth and energy-efficient process. Non-automated or non-optimum process control systems may lead to heat losses and moreover to unstable process conditions up to the point of more operational stops. This can cause increased fuel demand of the kiln for reheating the sintering zone. Automated computerised control systems are significant measures to optimise the combustion process and conditions. Today, all modern kilns are equipped with such systems.

Both raw materials and the fuel mix can be improved through analysis of chemical and physical characteristics. Besides automating the weighing and blending processes, other parameters like air flow, 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. Moreover, decreased energy demand under process controlled mill operation (vertical roller mill and ball mill) has been reported. Typical parameters controlled in such systems are: separator speed and fresh feed rate.

The electrical energy saving and the product quality can hereby be enhanced. Thermal and electrical energy savings relating to the use of control systems compared to a cement plant without such systems may vary typically between 50 to 200 MJ/t cli and 0 to 2.5 kWh/t cem. For certain countries (e.g. China) savings up to 290 MJ/t cli have been reported. Often, a payback period of 2 years is typical for control systems. However, it should be mentioned that the reduction of thermal and electrical energy demand strongly depends on the technical equipment, the status of the plant, the availability of the plant and the qualification of the operating staff.

Impact on energy efficiency

thermal: decrease of 50 to 200 [MJ/t cli]   electric: decrease of 0 to 2.5 [kWh/t cem]

CO_2 reduction potential

direct: decrease of 4 to 17 [kg CO_2/t cli]   indirect: decrease of 0 to 1.25 [kg CO_2/t cem]

Material input

not applicable

The main influencing parameters are

- 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 cem]	Investment [Mio €]	Operational [€/t cem]
2015	0.25 to 5.0	0.1 to 0.6 decrease	0.25 to 5.0	0.1 to 0.6 decrease
2030	0.25 to 5.0	0.1 to 0.7 decrease	0.25 to 5.0	0.1 to 0.7 decrease
2050	0.25 to 5.0	0.2 to 0.9 decrease	0.25 to 5.0	0.2 to 0.9 decrease

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

Conditions, barriers, constraints

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

3.19 Technology Paper No. 19: 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 can be reduced through the installation of variable speed drives. Dampers have the least energy efficiency of the available controls that can be retrofitted. The most energy efficient control 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. This means that the reduction to 80% of the rotational speed of a unit leads to energy savings of almost 50%. Frequency controlled equipment is used more and more in cement plants, but the application may vary widely depending on electricity costs. In particularr motors like the drives of big fans (e.g. ID fan, cooler fan, kiln exhaust fan) are often equipped with variable speed drives.

The power use in the reference cement plant is 104 kWh/t cem t 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. Assuming a low degree of implementation, power savings may vary considerably at a plant, ranging from 3 to 9 kWh/t cem. This range represents general figures based on experience which do not apply to new cement plants.

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 practice between 7 to 60%). Additional benefits of variable speed drives are the process controllability via process control systems, reduced maintenance costs, the availability and reduced motor noise, and the elimination of fan vibration. On the other hand, energy savings may be limited if the kiln is usually operated at its maximum capacity.

Impact on energy efficiency

thermal: not applicable [MJ/t cli]   electric: decrease of 3 to 9 [kWh/t cem]

CO_2 reduction potential

direct: not applicable [kg CO_2/t cli]   indirect: decrease of 1.5 to 4.5[kg CO_2/t cem]

Material input

not applicable

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 the cube of rotational speed
- CO_2 intensity of (external) power supply

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	0.25 to 0.35 (1.000 kW)	0.3 to 0.8 decrease
2030	not applicable	not applicable	0.25 to 0.35 (1.000 kW)	0.3 to 0.9 decrease
2050	not applicable	not applicable	0.25 to 0.35 (1.000 kW)	0.3 to 1 decrease

Remarks: The price is strongly dependent on the power requirement of the specific speed drive. The 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, constraints

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

3.20 Technology Paper No. 20: Auxiliary system efficiency

Compressed air is the third most important energy carrier in the cement industry, immediately after heat and power. Moreover, it is frequently considered one of the most inefficient and expensive forms of energy in the industry. Often around 90% of the energy necessary for its generation is lost in motor losses and waste heat. The generation of compressed air can represent more than 50% of power consumed by cross-sectional technologies in a cement plant, which include compressed air, lighting and acclimatisation of technical buildings and administrative offices. However, cross-sectional technologies represent only up to 5% of the total power consumption of a cement plant. Up to 20% efficiency gains can be obtained after the optimisation of compressed air systems. The correct design of the compressor units in accordance with the air requirement of the plant in conjunction with a centralized control system capable of managing demand fluctuations are among the most important measures that can be undertaken to improve efficiency. The pressure level to which compression is required depends on the consuming units (pressure level and volume flow), as well as on the design of the pipe network (pressure drop). The increase of 1 bar in the pressure level may lead to an increase of 6 to 8% of energy expenditure. The elimination of leakages, unplugging of decommissioned facilities and a differential pressure control system of the bag-filters cleaning system are among the measures able to reduce compressed air consumption.

Cement plants can have from 350 up to more than 1000 motors in operation (incl. conveyors, pumps, small fans and blowers), depending on the size of the plant and the process technology. The replacement of standard efficiency (IE1) by premium efficiency motors (IE3) can represent up to 9% nominal efficiency gains, depending on the size of the motor. Motors with higher installed power have however lower potential efficiency gains (up to 2%).The substitution of motors is usually done in a stepwise fashion, because spare motors stored in the plant cannot be simply ignored and disposed of. Therefore, a policy of purchasing only premium efficiency motors (Class IE3) when standard efficiency motors need replacing is advisable most of the time. The exception may be small motors with short operation times, where the purchase of a class IE3 motor may not be economically justifiable. The payback of this kind of investment is closely related to the operating time of the motor, purchase price and electricity tariff.

Lighting represents only an insignificant portion of the total power consumed in a cement plant (around 1%). Lighting technologies differ in their lifetimes, efficiencies (Lumen/Watt) and potential applications, which must be carefully assessed before undertaking any change from one technology to another. Moreover, the optimisation of lighting systems must always comply with local regulations, which may also narrow the potential energy gains from country to country. The design of the buildings and geographical localisation of the plant also impacts the need for artificial lighting. Up to 25% energy savings can be observed after the correct dimensioning and proper control of lighting systems and the replacement of standard light fixtures by energy efficient ones.

Impact on energy efficiency

thermal: not applicable [MJ/t cem]   electric: decrease of 3 to 5 [kWh/t cem]

CO$_2$ reduction potential

direct: not applicable [kg CO$_2$/t cem]   indirect: decrease of 1 to 3 [kg CO$_2$/t cem]

Material input

not applicable

The main influencing parameters are

- Initial level of implemented motors, compressed air and lighting system in the plant
- Correct design and maintenance (motors, lighting and compressed air system)
- Layout, localisation of the plant and cement manufacturing technology
- Financial incentives and national policies (motors, lighting and compressed air system)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	depends on measure/technology	depends on measure/technology	depends on measure/technology	0.2 to 0.4 decrease
2030	depends on measure/technology	depends on measure/technology	depends on measure/technology	0.3 to 0.5 decrease
2050	depends on measure/technology	depends on measure/technology	depends on measure/technology	0.3 to 0.6 decrease

Remarks: In retrofits the investment level strongly depends on the technology installed in the plant and its current condition. An assessment of the local conditions of the cement plant is fundamental to better define the investment needs and potential gains. Only the costs allocated to compressed air, lighting and high efficiency motors were considered in the estimation of operational costs. Depreciation, interest and inflation are not included.

Conditions, barriers, constraints

- Economics are dependent on electrical power price
- Local lighting regulations may constrain potential energy gains.

3.21 Technology Paper No. 21: Energy management

A systematic approach for increasing the energy efficiency of cement plants is the implementation of energy management systems. This implies the performance of energy audits by qualified internal personnel or by external providers.

Energy management systems are implemented to develop an energy policy for the whole company and establish objectives, targets and action plans to reduce energy use in accordance with the organization's energy policy. The energy management sets a focus on continuous monitoring and the potential for the improvement of energy use, its management, and on the implementation of energy efficiency measures. However, the energy saving is then not related to the implementation of energy management itself, but to the application of technologies with potential for energy savings for cement production (see other Technology Papers).

An important aspect is the awareness and training of the staff about energy use, company objectives and measures for energy savings. Changes in staff awareness, behaviour and attitude can have a significant impact. The use of automation and control systems can often improve overall energy efficiency (Technology Paper No. 20). Another important aspect is that the energy use of all relevant utilities (big motors, drives, pumps, etc.) is measured and continuously monitored with regard to their opportunities for improvement. In many countries requirements for energy efficiency and/or energy management exist for industrial plants.

International standards like ISO 50001 can be used as a guideline to implement and maintain an energy management system. The system follows a plan-do-check-act-cycle. The application of the system involves the establishment of a baseline and the monitoring of energy performance indicators. Management audits are an element for checking the effectiveness of the system.

Technical energy audits and reviews are an important step for identifying the potentials for further energy savings. A complete energy audit for a cement plant would include all relevant energy aspects and energy performance indicators:

- Evaluation of the energy demand (fuel and electricity) at the plant including raw material quarrying and preparation, clinker burning and cooling, cement and fuel grinding as well as auxiliaries based on information provided by the plants
- Evaluation of plant design with regard to energy aspects
- Evaluation of energy management of a company or plant
- Assessment of these characteristics in comparison with state-of-the-art cement production

Impact on energy efficiency

thermal: not applicable [MJ/t cem]   electric: not applicable [kWh/t cem]

CO$_2$ reduction potential

direct: not applicable [kg CO$_2$/t cem]   indirect: not applicable [kg CO$_2$/t cem]

Material input

not applicable

The main influencing parameters are

- Energy policy of the company
- Energy prices
- Incentives by legal regulation i.e. reduction of energy taxes or fees

Cost estimation

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

Remarks:
Energy management: No direct energy saving, but determination of technologies and potential for energy savings for cement production

Conditions, barriers, constraints

- Available financial funds for investment in energy saving measures
- Conflicting objectives for plant operation, i.e. product quality
- Knowledge about energy saving technologies, training
- Staff awareness.

3.22 Technology Paper No. 22: Optimised cement plant operation with renewable power

The share of electrical energy coming from renewable energy sources (wind, hydro, solar, biomass etc.) has been growing worldwide in the recent years. Agreements to limit global warming, which were made at the Paris climate conference 2015, suggest an even higher growth rate of renewable power in the years ahead. Wind and solar energy sources, however, depend on current local weather conditions. This makes their availability subject to fluctuations and adds a significant degree of unpredictability when it comes to the management of energy supply. During strong winds it occurs that not the entire energy can be fed into the grid and remains unused. The reason for such energy losses is a temporal mismatch between supply and demand or the electrical overload of power grids which are unable to handle additional electricity. Current storage capacities for electrical energy are often limited, very costly and related to efficiency losses. A growing share of renewables in electrical power production demands more flexible energy management strategies and the inclusion of demand side management, which can react to fast changing grid power supply and demand.

Traditionally, cement producers coordinate their electrical power-intensive processes with local grid operators regarding the operating times and duration. Often this results in operating the raw and cement mills only temporarily at night (e.g. 8 of 24 h), when the energy demand and prices are lower. Many cement plants have dedicated schedules and procedures for planning electrical energy demand well in advance and thereby already contribute to the demand side management of grid electricity. In order to further minimise the amount of discarded energy from renewables, additional management strategies and options for flexibility are envisaged.

On the cement plant's demand side, a flexible grinding approach could be used for raw meal production and cement manufacturing as power intensive processes. Free or increased silo and mill capacities are crucial in making flexible grinding possible. The management of silo and production capacities could then be utilized similar to a battery and to make optimal use of excess renewable energy. A decrease in demand during periods of lack of electrical energy supply could decrease the need for power production from fossil fuels. The mills should be able to grind a maximum amount of material at times of abundant renewable energy so that the clinker production can continue without any stoppages. The main drawbacks are a less efficient use of the mill and silo capacities and that the forecasting period and the peak load times can be too short for a start-up of the mill and for a continuous mill operation. An on-off operation of mills would increase energy losses, the wear of equipment, maintainance and some amounts of product with uncertain product quality. The minimisation of on-off operations must therefore be part of a management strategy for the efficient, flexible use of renewable energy for cement production and an energetically optimised cement plant.

For the production of electrical power in some cases a cement plant's existing emergency power equippment can be used to stabilise the availability of grid power in the case of fluctu-

ating renewable supply. Some cement producers invest in wind farms or solar plants in order to directly use renewable energy for cement production. Projects directly supplying renewable power to cement plants or projects in a construction phase are found worldwide, e.g. in Bulgaria, Egypt, Germany, India, Marocco, Mexico. In one example a wind farm is planned to initially cover up to 40% of a cement plant's power demand, and higher rates are expected in the future.

Impact on energy efficiency

thermal: not applicable   electric: not available, increase possible

CO_2 reduction potential

direct: not applicable   indirect: decrease of 2 to 18 [kg CO_2/t cem]

The CO_2 reduction potential was calculated based on the assumption of an average 0.5 h to 4 h per day mill operation with surplus renewable electrical power as substitution for electrical power produced from fossil fuels.

Material input

not applicable

The main influencing parameters are

- Additional production and silo capacities
- Availability of renewable electrical energy and surplus thereof
- Power supply infrastructure
- Plant location and wind/solar conditions

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	up to 25	not available	up to 60	not available
2030	up to 25	not available	up to 60	not available
2050	up to 25	not available	up to 60	not available

Remarks: Investment costs for new installations consider only the additional cost for selecting higher capacities for mills and silos than normally required for a 6000 tpd plant. The investment costs for a retrofit consider capacity extensions of raw and/or cement mills as well as raw and/or cement silos in order to produce a maximum amount at times of surplus renewable energy. Operational costs will decrease, but cannot be estimated due to significant regional differences in price policy for surplus electrical grid energy.

Conditions, barriers, constraints

- Cost for unused capacity of mills and silos
- High frequency of power load fluctuations and short forecasting periods

- Efficiency losses by on/off operation (wear of equipment, maintainance, product with uncertain quality)
- Low share of renewable energy in electrical energy mix
- Investment in renewable energy production.

3.23 Technology Paper No. 23: Cement grinding with vertical roller mills and roller presses

50 to 65% of the electric energy used for cement production is spent on raw material and finish grinding. Ball mills still account for the majority of mills installed in cement plants but on a global level among new installations today the vertical roller mill (VRM) has taken over the lead. A significant reduction of the specific energy demand for cement grinding can be achieved by grinding either in vertical roller mills (VRMs) or high pressure grinding rolls (HPGRs) in addition to existing ball mills or by a complete substitution of these mills. Theoretically the specific energy demand related to ball mills amounts to 70% for VRMs and up to 50% for stand-alone HPGRs. Saving potentials are only limited by the quality requirements of the final product. A fineness of up to 5500 Blaine in VRMs and up to 4500 Blaine in HPGRs can be achieved, but the particle size distribution of the products is different to ball mills. High-pressure comminution typically results in narrow size distribution, which can be problematic in terms of water demand or early strength but can also be advantageous for separate grinding and blending. In order not to compromise quality the HPGR is often used in combination with a ball mill, leading to a much more flexible but also far more complex grinding system. In this case the saving potential reaches up to 30% with an additional increase of throughput by up to 80% compared to single-stage grinding in ball mills. Despite this it has to be taken into account that the application of VRMs and HPGRs is connected to high capital costs and requires additional maintenance efforts.

Impact on energy efficiency

thermal: not applicable   electric: decrease of 5 to 14 [kWh/t cem]

CO_2 reduction potential

direct: not applicable   indirect: decrease of 2.6 to 6.8 [kg CO_2/t cem]

Material input

not applicable

The main influencing parameters are

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- CO_2 intensity of the power production equivalent to the retrenchment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	20 to 30	0.4 to 1.1 decrease	not applicable	not applicable
2030	20 to 30	0.5 to 1.3 decrease	not applicable	not applicable
2050	20 to 30	0.6 to 1.5 decrease	not applicable	not applicable

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time. The influence of increased maintenance efforts, effects on product quality, additional thermal energy for drying and a higher complexity of operation have not been considered. The evaluation of reduced energy demand is based on raw and cement grinding.

Conditions, barriers, constraints

- Vibration can impact stable operation (depending on feed properties and product fineness)
- Sufficient dehydration of sulphate agents cannot always be ensured due to low residence times
- Additional thermal energy required for additive drying
- Different particle size distribution compared to ball mills
- Durability is limited by wear elements.

3.24 Technology Paper No. 24: High efficiency separators

Open-circuit mills are not, or only with high power demand able to achieve a product fineness of more than 3500 Blaine. Therefore, they are connected to adjustable air separators and operated in closed 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. These feature optimised air ducts and additional external air circuits. The high separation efficiency leads to a higher proportion of 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 by 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%. To ensure process reliability, product quality, 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 complex process interactions.

Impact on energy efficiency

thermal: not applicable   electric: decrease of 2.3 to 4.5 [kWh/t cem]

CO_2 reduction potential

direct: not applicable   indirect: decrease of 1.1 to 2.3 [kg CO_2/t cem]

Material input

not applicable

The main influencing parameters are

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- CO_2 intensity of the power production equivalent to the retrenchment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	2	0.2 to 0.4 decrease	2	0.2 to 0.4 decrease
2030	2	0.2 to 0.4 decrease	2	0.2 to 0.4 decrease
2050	2	0.2 to 0.5 decrease	2	0.2 to 0.5 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, withconstant specific costs over time. It considers the savings in electrical energy based on an application to cement grinding. Impacts on product quality and increased maintenance effort were not considered.

Conditions, barriers, constraints

- Enhancement of the understanding of the grinding process
- Measurement and control techniques
- Workability of grinding aid
- Separator technology.

3.25 Technology Paper No. 25: Optimisation of operating parameters of ball mills

50 to 65% of the electric energy used for cement production is spent on raw material and cement grinding. Ball mills still account for the majority of mills installed in cement plants. An optimisation of the large number of established ball mills implies high saving potentials. The adaption of operating parameters represents an attractive approach due to the fact that almost no additional capital costs are required. Parameters which hold potential energy savings are the material filling level and the ball filling degree, the combination of the ball charge, liner design and adjustment of intermediate and outlet walls, and the adjustments of the separator. Standard optimisation methods include meter sampling along the grinding path and separator sampling. Through determination of the particle size distribution reduction potentials can be revealed. In addition, enhanced measures have been developed which allow a more directed control of the grinding process. These includes electric ears with a downstream frequency analysis or online monitoring systems for the discharge of the mill. The main problems are the complex interdependencies between the parameters mentioned. 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 have proven to be the methods of choice for achieving further understanding.

Impact on energy efficiency

thermal: not applicable   electric: decrease of 0.5 to 3.6 [kWh/t cem]

CO_2 reduction potential

direct: not applicable   indirect: decrease of 0.3 to 1.8 [kg CO_2/t cem]

Material input

not applicable

The main influencing parameters are

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- CO_2 intensity of the power production equivalent to the retrenchment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	0.015 to 0.025	0.1 to 0.3 decrease
2030	not applicable	not applicable	0.015 to 0.025	0.1 to 0.4 decrease
2050	not applicable	not applicable	0.015 to 0.025	0.1 to 0.4 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time. It considers the savings in electrical energy as well as reduced cost for wear. Mill optimisation can be done only once.

Conditions, barriers, constraints

- Enhancement of the understanding of the grinding process
- Effective methods for modelling and simulation of the comminution
- Measurement and control techniques
- Measurement expenditure.

3.26 Technology Paper No. 26: Separate grinding of raw material components

For the preparation of the raw mix for cement clinker production it is usually necessary to add different corrective components to the mix. Normally the grindability of the diverse constituents in the raw mix differs. This results in an accumulation
of components with worse grindability, a higher specific energy demand for comminution, and lower through-put of the combined grinding of all the components. Therefore, it can be efficient to grind the raw material components separately. If different mill systems are available it is best to assign the materials of the largest amounts to the most efficient system. Sufficient drying always has to be ensured.

The most common application of this would be the separate grinding of sand or slag, which are both much harder to grind and more abrasive than traditional raw materials. The 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 of the 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 can be ground more finely than necessary and the hard components (often sand) are not ground sufficiently fine, separate grinding would enable the production of a raw meal with differentiated fineness of different components with different impacts of the fineness on burnability. This would be a very site-specific effect and hard to quantify generally.

Impact on energy efficiency

thermal: not applicable   electric: decrease of 0.8 to 1.7 [kWh/t cli]

CO_2 reduction potential

direct: not applicable   indirect: decrease of 0.4 to 0.9 [kg CO_2/t cli]

Material input

not applicable

The main influencing parameters are

- Properties of raw material from quarry
- Grindabilty of raw mix components
- Grinding technolgy
- CO_2 intensity of the power production

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	10 to 20	0.17 decrease to 0.04 increase	2 to 5	0.19 decrease to 0.04 increase
2030	10 to 20	0.19 decrease to 0.03 increase	2 to 5	0.20 decrease to 0.03 increase
2050	10 to 20	0.21 decrease to 0.02 increase	2 to 5	0.23 decrease to 0.02 increase

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time. The retrofit is based on the assumption that grinding equipment and the silo capacity for separate grinding are already available. The cost estimation for new installation is based on the assumption that one raw mill is already available and only one additional small mill has to be installed. No additional personnel costs have been calculated. Operational costs include maintenance costs for the additional grinding system as well as possible reduction of component wear and the cost difference for electric energy.

Conditions, barriers, constraints

- High investment costs compared to a very limited effect if installation of a 2nd mill is necessary
- Increase of operational costs can be significantly higher than the cost savings for electric energy
- Usually the raw material grinding is processed with one grinding system. Separate grinding requires different grinding plants and, if the comminution cannot be done at the same time, additional storage capacity.

3.27 Technology Paper No. 27: Advanced grinding technology

Comminution processes account for up to 70% of the electric energy demand for clinker and cement production. Energy utilisation in comminution with currently available technology is low. Therefore, the further development of grinding technologies theoretically holds huge saving potentials. In practice, high pressure comminution is replacing grinding in ball mills step by step, but theavailable mills are still not able to achieve optimum energy utilisaation.

ECRA has taken on this challenge and has established a research project dedicated to efficient grinding in the cement industry. The project is pre-competitive and will examine "Future grinding technologies" for the cement manufacturing process. It involves cross-sectorial stakeholders including equipment suppliers.

Prototypes and industrial demonstrators have already been developed and will be available on the market within the next years. The modifications of 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, their limitation in capacity, the wear of stirring devices and the increased complexity of the gear have to be taken into account. With increasing product fineness in many markets the use of specialised equipment for (ultra-)fine grinding is becoming more attractive. And there is also an increasing interest in small flexible and movable mill systems. Today there are already a variety of mills available for dry fine grinding of cement, but there is still only limited experience with these types of equipment. Furthermore, the material handling of very fine materials is difficult. In addition, there are a variety of grinding technologies still at the stage of research and development. Contact-free grinding systems, like e.g. the vortex technology, seem to be very attractive considering the problems related to the durability of wear elements. So far, ultrasonic-comminution has not proven to be able to comminute large amounts of hard and brittle material to the relevant fineness. High voltage power pulse fragmentation is under research in the mining industry, but an application to the cement industry is not expected short or mid-term. A completely different approach is low temperature comminution. A statement regarding energy efficiency, CO_2 and cost savings is not yet possible.

Impact on energy efficiency

thermal: not applicable   electric: not available

CO_2 reduction potential

direct: not applicable   indirect: not available

<u>Material input</u>

not applicable

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

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- Physical limitations for energy transfer
- Material science and grinding technology
- Durability of wear elements
- CO_2 intensity of the power production equivalent to the retrenchment
- R & D efforts

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: General cost estimation not possible at the current stage of development.

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

- 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.

3.28 Technology Paper No. 28: Separate grinding and blending by fineness

Cement is ground to high fineness to enhance the cement properties (e.g. strength development). In most cases the very high fineness causes overgrinding of the product. As a result, agglomerations occur and the specific energy demand increases. Very fine particles below 8 µm are responsible for early strength development. Vice-versa, coarser particles need more time for hydraulic reaction and are primarily responsible for the general strength development.

Furthermore, high amounts of very fine particles are not necessary in all cases to achieve the cement properties. It has emerged that in many cases an intermediate product in combination with a small amount of very fine material can also achieve the required product quality. The amount of coarse cement particles can be produced on high pressure grinding devices (e.g. Vertical Roller Mills (VRMs), or High Pressure Grinding Rolls (HPGRs) to decrease the electrical energy demand compared to ball mills significantly. Grinding of the very fine fraction can be performed on very suitable grinding devices (e.g. dry operating stirred media mills), which are able to produce fine particles much more efficiently than grinding devices used in the cement industry today.

The use of BAT grinding technology in combination with fine grinding devices to blend cements will allow significant savings (up to 8%) of the electrical energy demand in cement grinding. Moreover, the demand of grinding aids will decrease, due to the production of coarser cement (not considered in calculations). Due to the production of very fine cements the technique is not directly applicable for cements of low to medium strength classes. The range of cements produced in cement plants is very comprehensive. With the installation of a new VRM or HPGR the specific energy demand of low to medium strength class cements can also improve (not considered in calculations).

Impact on energy efficiency

thermal: not applicable   electric: decrease 1.4 to 3.2 [kWh/t cem]

CO_2 reduction potential

direct: not applicable   indirect: decrease 0.7 to 1.6 [kg CO_2/t cem]

Material input

not applicable

The main influencing parameters are

- Properties of clinker and other main constituents
- Grindabilty of the constituents
- Grinding technolgy
- Required cement properties
- CO_2 intensity of the power production

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not available	not available	not available	not available
2030	29 to 38	0.04 to 0.4 decrease	4 to 8	0.04 to 0.36 decrease
2050	29 to 38	0.05 to 0.45 decrease	4 to 8	0.06 to 0.41 decrease

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time. The retrofit is based on the assumption that one VRM or HPGR and at least one blending silo are already available and only one additional small fine grinding device is installed.
- The cost estimation for new installation is based on the assumption that a new VRM, a new multi-chamber blending silo and a new fine grinding device have to be installed.
- Depreciation, interest and inflation are not included in the operational costs. No additional personnel costs have been calculated. Operational costs include maintenance costs for the additional fine grinding system, the possible reduction of component wear and the cost difference for electric energy.

Conditions, barriers, constraints

- High investment costs compared to limited effect if installation of a 2nd mill is necessary
- Separate grinding requires different grinding plants and, if the comminution cannot be done at the same time, additional storage capacity is required
- Not appropriate for the production of cement types of low fineness.

3.29 Technology Paper No. 29: Increased cement performance by optimised particle size distribution (PSD)

In many cases multi-composite cements are inter-ground in one mill. As a result the constituents with a lower grindability index (e.g. limestone) will accumulate in the fine fraction, while on the other hand constituents which are hard to grind can be found in the coarse part of the product. Interground fines contain a high amount of overground particles and agglomerations. Therefore, it is not possible to control the particle size distribution (PSD) of single constituents of the cement, but during separate grinding and blending the full potential of optimised product PSD is also not always reached.

The separate grinding and blending of the main constituents enables a new degree of freedom. It is possible to control the position of clinker and inert, puzzolan and latent hydraulic constituents in the PSD. Since different mill types produce different PSD at various fineness levels an overall product PSD can be designed by choosing different mill types for different components. The optimisation can focus on
- optimisation of the cement properties or
- reduction of the specific energy demand or
- increase of the substitution rate of clinker.

It has been observed that through optimisation of the PSD the portion of other constituents (like limestone or slag) could be increased by up to 5% without compromising on strength. Thus thermal energy (up to 183 MJ/t savings) and the electrical energy demand can be reduced depending on the amount of substituted clinker. Moreover, with optimisation of the cement properties higher strength can be achieved with less energy demand due to appropriate distribution of the constituents in the cement PSD. Furthermore, optimisation of the cement PSD can affect the cement properties, particularly the workability / water demand and durability of concrete, which increases the sustainability of the cement and concrete systems.

Impact on energy efficiency

thermal: decrease 0 to 183 [MJ/t cem]   electric: decrease 1.5 to
                                                             increase 0.1 [kWh/t cem]

CO_2 reduction potential

direct: decrease 0 to 45 [kg CO_2/t cem]   indirect: decrease 0.72 to
                                                                   increase 0.04 [kg CO_2/t cem]

Material input

Increased use of alternative main constituents, numbers not available

The main influencing parameters are

- Properties of clinker and other main constituents
- Clinker substitution rate
- Grinding technolgy
- Required cement properties
- CO_2 intensity of the power production

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	3 to 8	decrease 1.68 to increase 0.09	not applicable	decrease 1.53 to increase 0.10
2030	3 to 8	decrease 1.98 to increase 0.09	not applicable	decrease 1.80 to increase 0.10
2050	3 to 8	decrease 2.30 to increase 0.09	not applicable	decrease 2.09 to increase 0.10

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time. The retrofit is based on the assumption that different mills and at least one multi-chamber blending silo are already available. The cost estimation for new installation is based on the assumption that a new multi-chamber grinding silo has to be installed.
- Depreciation, interest and inflation are not included in operational costs. No additional personnel costs have been calculated. Operational costs include the cost difference for electrical energy.

Conditions, barriers, constraints

- Increase of the operational costs by additional blending and transport costs possible
- Additional effort in quality control.

3.30 Technology Paper No. 30: Optimised use of grinding aids

In nearly all mills for cement grinding and also in a variety of raw mills, grinding aids are used in order to increase the efficiency of the grinding process. Grinding aids are solid or liquid substances like amines (e.g. Mono-, Di- or Tri-ethanolamine) or glycols (e.g. propylene- or ethylene-glycole) that are added in small quantities to the mill feed. Especially with increasing product fineness it is essential during comminution to not only produce new surfaces but also control these. Due to electrostatic forces newly created surfaces tend to stick together and form agglomerates (secondary particles) or coatings which have a damping effect during comminution. Grinding aids are chemisorbed by the particles and have a neutralizing effect on the surface charges. Although they do not actively increase particle breakage, their use increases process efficiency by avoiding the build up of coatings and through better material transport and increased separator efficiency. But grinding aids can also alter the particle size distribution (PSD) of the product and can have an effect on strength development.

It is therefore necessary to optimise the use of grinding aids (type and amount) by taking a holistic approach and considering the comminution and separation process as well as the product properties. In many cases a grinding aid is primarily applied in order to reduce coatings inside of mills. But since the residence time in the mill and the separator performance change, the PSD is altered, leading to changed product properties. Better PSD allows a reduction of fineness which again allows modification of the process parameters. The optimisation process is therefore iterative and complex and has to be applied to each type of grinding aid. For intergrinding the optimisation by cement type holds additional potential since different main constituents react differently with the grinding aid.

Through the appropriate selection of a grinding aid and the optimisation of the cement grinding process and the product, a saving potential of 2 to 5% is expected, while the amount of required grinding is not expected to rise significantly. A positive effect on raw material grinding is expected to be much lower compared to finish grinding.

Impact on energy efficiency

thermal: not applicable   electric: decrease of 0.5 to 2.3 [kWh/t cem]

CO_2 reduction potential

direct: not applicable   indirect: decrease of 0.3 to 1.1 [kg CO_2/t cem]

Material input

Grinding aid   0.0002 to 0.0005 [t/t cem]

The main influencing parameters are

- Product fineness and composition
- Properties of main constituents
- Product properties (strength development, workability, water demand)
- Type of mill and separator
- Performance of available grinding aid

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	not applicable	0.03 to 0.18 decrease
2030	not applicable	not applicable	not applicable	0.04 to 0.20 decrease
2050	not applicable	not applicable	not applicable	0.05 to 0.24 decrease

Remarks: The cost estimation is based on a clinker capacity of 2 Mio. t/a, dosing system for grinding aid already available, with constant specific costs over time; Taken into account are the savings in electrical energy based on an application to raw material grinding (min) and cement grinding (max). Possible cost reduction or increase due to change in type of grinding aid, increase or decrease of amount is not considered.

Conditions, barriers, constraints

- Type of available grinding aid
- Local standards and regulations
- Transport, packing and de-dusting equipment
- Product portfolio.

3.31 Technology Paper No. 31: 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 blending by the separate or inter-grinding of clinker with granulated blast furnace slag as another main constituent. As less clinker is needed per ton of cement, CO_2 emissions from fuel combustion and from the decarbonation of limestone can partially be saved.

The production of cements with GBFS as a main constituent requires additional fuel for drying as well as additional electricity for grinding (depending on higher fineness). However, the use of GBFS does not lead to a significant increase 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 demand 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 the reduced clinker proportion.

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. On the other hand, the use of GBFS as a main constituent of cement can lead to higher long-term strength and improved resistance to chloride ingress, alkali-silica-reaction and sulphate attack. Cements with higher amounts of GBFS are often suitable as cements releasing low heat of hydration, e.g. for massive constructions.

As an example, the European standard EN 197-1 defines 9 cement types with up to 95 mass% GBFS and up to 80 mass% of a combination of GBFS and pozzolana (where the maximum amount of GBFS is 50 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 being investigated and discussed at present in many countries as well as e. g. on a European level. However, in practise the amount of GBFS in technically used cements usually ranges from 30 to 70 mass%.

The availability of GBFS mainly depends on pig iron production. Currently about 280 Mio. t/a GBFS are produced worldwide. Slag production data on a global level are unavailable, but it is estimated that the annual world iron slag output in 2014 was in the order of 310 to 370 Mio. tons, and steel slag about 170 to 250 Mio. tons, based on typical ratios of slag to crude iron and steel output.

In future, blast-furnace slag and fly ash can be used in ternary and quaternary mixes with steelworks slag / acid blastfurnace-slags and clinker to overcome a lack of hydraulicity of certain slag types, and to increase the availability of slags.

The estimations are based on GBFS content in cement of 30 to 70 mass% in comparison to the reference plant data (see "key assumptions" in Annex).

Impact on energy efficiency

thermal: decrease of up to 1590 [MJ/t cem]   electric: increase of up to 10 [kWh/t cem]

CO_2 reduction potential

direct: decrease of up to 390 [kg CO_2/t cem]   indirect: increase of up to 5 [kg CO_2/t cem]

Material input

granulated blastfurnace slag   amount of material up to 0.70 [t/t cem]

The main influencing parameters are

- Availability (depends mainly on steel production, level of slag granulation, use of GBFS in concrete or geopolymers)
- Quality and price (incl. logistics) of GBFS

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	5 to 10	decrease 7.2 to increase 0.8
2030	not applicable	not applicable	5 to 10	decrease 9.4 to increase 0.9
2050	not applicable	not applicable	5 to 10	decrease 11.7 to increase 1.1

Remarks:

- Capital costs are only relevant if extra storage capacity is necessary for GBFS and new cement types, and for technical equipment for the 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
- 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, and joint 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)
- Logistics
- Technical performance of concrete produced with cements containing GBFS (e.g. strength development, durability)
- Standards and regulations
- Market acceptance.

3.32   Technology Paper No. 32: High performance cements and concretes resulting in the reduction of CO_2

Often the reduction of cement content is mentioned as an essential measure for reducing the CO_2 emissions of concrete. In fact it is not the cement content, but the efficient use of Portland cement clinker which leads to success in this respect. The water-cement ratio is of substantially greater importance for the compressive strength of structural building concretes of usual composition than the cement strength class and the cement content. The cement content and the paste content have a strong influence on the workability, robustness and durability of concrete. The cement paste component causes a dense micro-structure which is of great importance for the concrete durability and guarantees the alkalinity of the concrete, which prevents the corrosion of reinforcing steel. For these reasons, minimum cement contents are defined in regulations and standards for concrete construction.

High or ultra-high-performance concrete (UHPC) is concrete with or without fibres, with a characteristic cylinder compressive strength of at least 130 MPa and a maximum grain size between 0.5 mm and 16 mm. Generally, water/cement ratios between w/c = 0.20 and w/c = 0.35 are used. Today, the cement used for UHPC is in most cases Portland cement. Such concretes lead to a decrease in the required amount of concrete in slim construction units. Although those concretes contain increased cement contents per t or m³, a potential CO_2 reduction can result related to the functional unit of the concrete construction element. This potential can be calculated by comparing normal concrete and UHPC on the level of functional construction elements, such as columns or bridge elements. The system boundaries are in most cases „product stage" (cradle to gate) + "construction process stage" (transport to the construction site and installation). An environmental factor between a decrease of 10% and an increase of 60% for comparing the global warming potential (GWP) of UHPC construction elements and normal concrete elements with the same functionality can be assumed.

The reasons for a - in most cases - higher GWP of UHPC construction are its high Portland cement and steel fibre contents. Therefore, the potential to reduce CO_2 is limited at the present time. One can expect that with the combination of clinker-efficient cements (Technology Papers No. 31 and 34 to 37) and UHPC, the potential of CO_2 reduction of UHPC will grow in the coming years. If the whole life cycle of a construction work or element is taken into account, UHPCs can be more CO_2 efficient than normal concrete as they are expected to be much more durable.

With regard to UHPC energy demand there are not enough reliable figures available at the moment. Since UHPC construction elements need less material, it is assumed that there is no significant impact on the energy demand for UHPC use.

An additional possibility with regard to facing the challenges of steel reinforcement corrosion through chloride ingress or carbonation is the development of concrete with non-corroding, non-ferrous reinforcements. This development began with "textile concrete" using alkali-

resistant glass fibres or meshes as reinforcements. In current research projects, glass is being replaced by carbon.

The development of very slim construction elements with the same functionality as normal steel-reinforced concrete elements can be promoted by using carbon as a reinforcement combined with the above described UHPC.

Another field of application is the strengthening of steel-reinforced concrete work by thin carbon concrete laminated layers. For this application, technical approvals are available and several construction projects have been realised in practise.

Impact on energy efficiency

thermal: not applicable [MJ/t cem]   electric: not applicable [kWh/t cem]

CO_2 reduction potential

direct: not applicable [kg CO_2/t cem]   indirect: not applicable [kg CO_2/t cem]

CO_2 reduction potential of using UHPC as an environmental factor:

2015: decrease of 10% to increase of 60%

2030*: decrease of 40% to increase of 10%

2050*: decrease of 50% to decrease of 10%

* For 2030 and 2050, the potential to replace Portland cement (OPC) in UHPC by cements with several main constituents and the optimisation of the fibre producing process have been taken into account.

Material input

not applicable [t/t cem]

Cost estimation

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

Conditions, barriers, constraints

- Workability and durability of concrete
- Minimum cement contents defined in the regulations and standards for concrete
- Standards for UHPC
- Practical experience with UHPC
- Development of UHPC with clinker-efficient cements and energy-efficient produced fibres.

3.33 Technology Paper No. 33: Impact of very high/very low lime saturation factor

The lime saturation factor (LSF) of Ordinary Portland Cement (OPC) clinker typically ranges between 92 and 102. Usual OPCs have LSFs of up to 97. Higher LSFs are generally required for fast setting OPCs with high early strengths. A change of the LSF by 1 relates to a change of the absolute CaO content of the clinker by about 0.2 to 0.3 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. Decreased energy demand 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 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 demand of the burning process. Additionally, lower LSFs can reduce the required amounts of valuable pure limestone in the raw meal, depending 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 increases with the fineness.

Impacts of lower LSFs and higher fineness 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 the fineness and chemical composition of all reactants.

The following estimations are based on a decrease in clinker LSF by 10 units.

Impact on energy efficiency (for an assumed decrease in LSF of 10 units)

thermal: decrease of 119 to 125 [MJ/t cem]   electric: increase of 9 to 25 [kWh/t cem]

CO_2 reduction potential (for an assumed decrease in LSF of 10 units)

direct: decrease of 19 [kg CO_2/t cem]   indirect: increase of 5 to 12 [kg CO_2/t cem]

Material input

Raw meal with LSF reduced by 10 units   nearly same amount (1,53) [t/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 demand for grinding to achieve a higher cement fineness
- Lower grindability of low-LSF (belite-rich) clinker

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	not applicable	increase 2.5 to 3.9
2030	not applicable	not applicable	not applicable	increase 2.6 to 4.0
2050	not applicable	not applicable	not applicable	increase 2.6 to 4.3

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.

3.34 Technology Paper No. 34: Further reduction of clinker content in cement by use of fly ash

Several main constituents beside 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). In particular calcareous fly ashes may have critical sulfate (SO_3) and/or free lime contents. Furthermore, many fly ashes contain higher amounts of unburned carbon or other unwanted components affecting their suitability for cement and concrete.

The use of fly ash as a cement constituent requires electricity for grinding or blending. Fly ash can also be added directly, e.g. into the classifier. On average this leads to a decrease of electricity consumption for the cement grinding process. The thermal energy demand of the cement production decreases almost linearly with an increase in the fly ash content.

The use of siliceous fly ash as a cement constituent can lead to improved workability, higher long-term strength and higher concrete density. The short-term strength of cements with fly ash as a main constituent may be diminished significantly. The fly ash content in technically used cements is usually limited to about 25 to 35 mass%. Fly ashes are used in significant amounts in concrete in some countries (USA, China, Germany), replacing cement and thereby lowering the specific CO_2 footprint of concrete. This manner of fly ash utilisation rivals its use in cement. However, the processing procedures applied for the production of fly ash cements in cement plants usually contribute to a somewhat higher exploitation of the fly ash performance.

The possibility to use fly ash as a constituent of cement depends strongly on the availability of fly ash. With respect to the CO_2 discussion, the future number and capacity of coal fired power plants is hardly predictable. Currently about 750 Mt/a of fly ash are produced worldwide. The ratios of fly ash utilisation in cement and concrete differ strongly in different countries or regions (Brazil ~60%, China ~60%, India ~45%, USA ~40%, EU ~20%).

The following estimations are based on fly ash contents in cement of 25 to 35 mass% in comparison to the reference plant data (see "key assumptions" in Annex).

Impact on energy efficiency

thermal: decrease of 0 to 360 [MJ/t cem]   electric: decrease of 2 to 15 [kWh/t cem]

CO_2 reduction potential

direct: decrease of 0 to 90 [kg CO_2/t cem]   indirect: decrease of 1 to 8 [kg CO_2/t cem]

Material input

coal fly ash   0.25 to 0.35 [t/t cem]

The main influencing parameters are

- Availability (depends mainly on coal combustion for production of electricity and on use of fly ash in concrete or geopolymers)
- Quality and price (incl. logistics) of the fly ashes
- Amount of fly ash in cement
- Durability of concrete produced with fly ash containing cements

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicaple	not applicaple	8 to 12	decrease 0.2 to increase 0.9
2030	not applicaple	not applicaple	8 to 12	decrease 0.2 to increase 0.2
2050	not applicaple	not applicaple	8 to 12	decrease 0.6 to decrease 0.3

Remarks:

- Capital costs are due to extra storage capacity for the fly ashes and the cements as well as the technical equipment for handling (grinding, 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, increased electricity costs for raw material and 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 fly ashes
- Logistics
- Technical performance of concrete produced with fly ash cements (e.g. workability, strength development, durability)
- Standards and regulations
- Further research is required concerning the reactivity of fly ashes in general and the use and handling of calcareous fly ash in cement
- Utilisation of fly ash in cement rivals its use in concrete; however, the effects on the specific CO_2 footprint of concrete is in the same order of magnitude for both applications.

3.35 Technology Paper No. 35: Further reduction of clinker content in cement by use of natural pozzolanas

The production of cements containing pozzolanic materials as a main constituent 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 which react in the presence of water at ambient temperature with dissolved calcium hydroxide ($Ca(OH)_2$) to form strength-developing calcium silicate and -aluminate hydrates. According to EN 197-1 the content of reactive silicon dioxide must be at least 25 mass%. The reac-tive alumina content is also of significance. A differentiation is made between natural pozzolanas ("P" acc. EN 197-1) and natural calcined pozzolanas ("Q" acc. EN 197-1, see Technology Paper 36). Natural pozzolanas are usually materials of volcanic origin or sedimentary rocks with suitable chemical and mineralogical composition (e.g. pumice or diatomite).

The production of cements with natural pozzolanas involves the pre-treatment of the pozzolana, such as crushing, drying and grinding, and the inter-grinding or mixing of the cement clinker with the pozzolanic material. The electric energy demand is assumed to be slightly lower because of the better grindability of most pozzolanas compared to the replaced clinker. The thermal energy demand of the cement production decreases almost linearly with an increase in the pozzolana. The partly vastly different properties of the cement are disregarded in this approach.

Cement properties diversify depending on the pozzolanic materials used, their chemical and mineralogical composition, their fineness and therefore their reactivity. Because the pozzolanas do not react as fast as the clinker, in general the early compressive strength of cement decreases when increasing the amount of natural pozzolanas. 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, improved chemical resistance and less efflorescence of hydration products.

The use of natural pozzolanas as a 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 pozzolanas from 6 to 55 mass% is possible. In practice the proportion of pozzolana in technically used cements is usually in a range of 15 to 35 mass%.

The availability of pozzolanas mainly depends on the local geological conditions. In 2003 only about 30 Mio. t pozzolanas were used worldwide, but only about 50% in cement and concrete industries. No currently reliable figures are available, but only a slight increase is assumed. A further increased use of pozzolanas for cement manufacturing will imply larger transport distances.

The estimations are based on pozzolana content in cement of 15 to 35 mass% in comparison to the reference plant data (see "key assumptions" in Annex).

Impact on energy efficiency

thermal: decrease of up to 360 [MJ/t cem]   electric: decrease of up to 3 [kWh/t cem]

CO_2 reduction potential

direct: decrease of up to 90 [kg CO_2/t cem]   indirect: decrease of up to 1.7 [kg CO_2/t cem]

Material input

natural pozzolanas   up to 0.35 [t/t cem]

The main influencing parameters are

- Type, availability, quality and price (incl. logistics) of the used pozzolanas
- Amount of pozzolana in cement

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	8 to 12	up to 2.9 decrease
2030	not applicable	not applicable	8 to 12	up to 3.5 decrease
2050	not applicable	not applicable	8 to 12	up to 4.1 decrease

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
- Operational cost savings depend on reduced fuel costs for clinker production, reduced electricity costs for kiln drives and bypass, and decreased electricity costs for cement grinding. They might increase due to the transport costs of the pozzolanic material.
- 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 reactivity) and (potentially) prices of the pozzolana
- Logistics
- Technical performance of concrete produced with blended cements (e.g. workability, strength development, durability)
- Standards and regulations
- Market acceptance.

3.36 Technology Paper No. 36: Further reduction of clinker content in cement by use of natural calcined pozzolanas

The production of cements containing natural calcined 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, but must be rated against CO_2 emissions from the calcination process.

Natural calcined pozzolanas used for cement production are usually thermally treated clays. By the release of physically and chemically bound water the mineral structures decompose. The resulting reactive silica and alumina compounds react in the presence of water at ambient temperature with dissolved calcium hydroxide ($Ca(OH)_2$) to form strength-developing calcium silicate and -aluminate hydrates. According to EN 197-1 the content of reactive silicon dioxide must be at least 25 mass%. Pure kaoline is well known as a suitable raw material, but for economic reasons clays of lower grade, probably as mixtures of several clay minerals will be of relevance.

The production of cements with calcined clay involves pretreatment of the clay, e.g. drying (release of up to 30 mass% water), crushing and calcination, followed by inter-grinding or mixing of the cement clinker with the pozzolanic material. Beside CO_2 emissions from the thermal energy demand for calcination, the decarbonation of carbonate impurities in the raw clays might also be considered. The electric energy demand is assumed to be slightly lower because of the better grindability of calcined clays compared to the replaced clinker. The frequently different properties of the cement are disregarded in this approach.

Because calcined clays of technical grade do not react as fast as the clinker, in general the early compressive strength of cement decreases with increasing calcined clay proportions. Expanded calcined clays could increase the water demand of the cement which must be compensated by concrete technology measures. On the other hand, calcined clay cements may show higher long term strength and improved durability due to a dense microstructure.

Up to now the use of natural calcined Pozzolanas is common only in a few countries and in very low market shares (e.g. Brazil with 3% of the national cement market). In the medium-term, the use of calcined clay cements will only be increased in areas where no suitable amounts of other active cement main constituents (slags or fly ashes) are available. In the long-term view, calcined clays are expected to become an important material group as the global availability of slags and fly ashes will not be able to cover the demand for cement main constituents. The geological availability of raw clays is comparably high all over the world.

According to EN 197-1, the production of various cement types containing natural calcined Pozzolanas ("Q") from 6 to 55 mass% is possible. In practice the proportion of calcined clays in technically used cements is usually in a range of 15 to 35 mass%.

Recent developments use synergetic effects of optimised combinations of calcined clays and ground limestone as supplementary cementitious material. It is stated that the co-addition allows a clinker reduction of up to 50% maintaining similar performance to existing cements.

The estimations are based on a calcined natural pozzolana content in cement of 15 to 35 mass% with or without additional 15 mass% of limestone in comparison to the reference plant data with 25 mass% of other cement main constitutants (see "key assumptions" in Annex).

Impact on energy efficiency

calcined clay without limestone

thermal: increase of up to 150 [MJ/t cem]   electric: decrease of up to 5 [kWh/t cem]

calcined clay combined with limestone

thermal: decrease of up to 380 [MJ/t cem]   electric: decrease of up to 7 [kWh/t cem]

CO_2 reduction potential

calcined clay without limestone

direct: decrease of up to 73 [kg CO_2/t cem]   indirect: decrease of up to 2.5 [kg CO_2/t cem]

calcined clay combined with limestone

direct: decrease of up to 180 [kg CO_2/t cem]   indirect: decrease of up to 3.7 [kg CO_2/t cem]

Material input

calcined clays   up to 0.35 [t/t cem]

(natural calcined pozzolana)

combined with limestone   up to 0.15 [t/t cem], in sum 0.50 [t/t cem]

The main influencing parameters are

- Type, availability, quality and price (incl. logistics) of the raw material (clay + limestone)
- Treatment and calcination energy requirement and costs
- Amount of pozzolana in cement, amount of limestone in cement

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not available	not available	8 to 12	up to 7.2 decrease
2030	not available	not available	8 to 12	up to 8.5 decrease
2050	not available	not available	8 to 12	up to 9.9 decrease

Remarks:

- Capital costs are due to extra storage capacity for the calcined pozzolana, the ground limestone and the cements as well as the technical equipment for handling and drying of the calcined pozzolana
- For the use of natural calcined pozzolana a calcination step will be necessary, which leads to costs for additional fuels and technical equipment
- The latter costs can be saved if the calcination takes place in distinct campaigns, using the kiln available
- Operational cost savings depend on reduced fuel costs for calcined clay instead of clinker production, reduced electricity costs for kiln drives and bypass, and decreased electricity costs for cement grinding. Savings are reduced by potential transport costs of the pozzolanic materials
- These costs need to be assessed on the basis of individual plants and cement types

Conditions, barriers, constraints

- Sources, availability (intensive land-use), quality (in particular homogeneity) and (potentially) prices of the raw clay
- Logistics, especially for calcination, storage and handling
- Technical performance of concrete produced with blended cements (e.g. workability, strength development, durability)
- Standards and regulations
- Market acceptance.

3.37 Technology Paper No. 37: Further reduction of clinker content in cement by use of other materials

A very simple and the most efficient method to reduce the clinker content of cement is the use of limestone. Limestone usually is located at the plant in sufficient qualities and quantities. The grindability of limestone is much better compared to clinker. Hence, limestone reduces CO_2 emission from fuel combustion and decarbonation as well as the thermal and electrical energy demand in direct proportion to its content in cement. Limestone-containing cements typically show reduced water demand leading to better workability of concrete. Cements with limestone have to be ground finer to achieve the same strength as Portland cement. The proportion of limestone in cement and the cement content are decisive for concrete's resistance to carbonation, chloride ingress, freeze-thaw etc. Therefore, EN 197-1 limits the proportion of limestone in cement to 35 mass%. Higher amounts of limestone are possible. The situation can be summarised by stating that sophisticated process engineering measures in the cement plant and equally sophisticated concrete technology measures (low-water concrete with appropriate addition levels of admixtures) in the concrete production would be necessary for the production and use of high-limestone cements (up to 50 mass% limestone). If these measures can be implemented under practical conditions then it will be possible for the concrete to achieve durability parameters that can meet the approval requirements. The robustness of these systems in construction work requires further verification.

Silica fume is an industrial by-product originating in the production of silicon and ferrosilicon alloys. It consists of very fine spherical particles of almost only amorphous silica. Due to its very high amorphous silica content and fineness, the pozzolanicity but also the water demand of silica fume are very high. Hence, EN 197-1 limits the proportion of silica fume in cement to 10 mass%. The world-wide availability of silica fume is limited.

Other pozzolanically reacting materials such as rice husk ash or palm oil ash are only of local relevance. Their availability is limited and depends on other industries. The suitabilty of further industrial by-products, residues and recyclates, that could basicly react like pozzolans, has been under research for several years. Until now, the limiting factor is always the worldwide availability in sufficient quantity and quality.

Burnt shale, finely ground, shows hydraulic and pozzolanic properties and hence combines the advantages of clinker and pozzolans for cement's compressive strength and concrete durability, but suitable raw shale is available only in some regions.

The estimations are based on limestone content in cement of 25 to 35 mass% in comparison to the reference plant data with 25 mass% of other cement main constitutants (see "key assumptions" in Annex).

Impact on energy efficiency

thermal: decrease of 0 to 360 [MJ/t cem]   electric: decrease of 0 to 5 [kWh/t cem]

CO_2 reduction potential

direct: decrease of 0 to 88 [kg CO_2/t cem]   indirect: decrease of 0 to 2.6 [kg CO_2/t cem]

Material input

limestone   0 to 0.10 [t/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 demand 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 cem]	Investment [Mio €]	Operational [€/t cem]
2015	not applicable	not applicable	8 to 12	0.4 to 2.7 decrease
2030	not applicable	not applicable	8 to 12	0.5 to 3.1 decrease
2050	not applicable	not applicable	8 to 12	0.6 to 3.7 decrease

Remarks:

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 bypass, 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.

3.38   Technology Paper No. 38: Alkali-activated binders

Alkali-activated binders are mostly 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" for such systems was first used by Davidovits in the 1970s to accentuate the relationship to geological materials. Nowadays the term is used for low calcium activated binders, e.g. based on metakaoline.

For a geopolymeric polycondensation suitable materials are alumosilicates which can be of natural (metakaolin, natural pozzolana) or industrial origin (fly ashes, granulated blast furnace slags - GBFS). In any case the availability of these materials is limited. As a consequence, even if technical barriers might be overcome, alkali-activated binders will only be able to be produced regionally in limited quantities for niche products. Chemically such binders 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). Variations in composition and moisture of the reactive solid component as well as the temperature can cause significant variations in quality, e.g. strength development and durability of the binder. In particular the sensitivity to dilution with water makes polymerisation difficult to use in ordinary concrete applications, especially since concrete aggregates are often wet to different extents. The inherently low content of bound water in fully-reacted alkali-activated binders generates an excellent fire resistance and relatively low drying shrinkage.

Until now, alkali-activated binders have been produced mostly for demonstration purposes and have only been used in non-structural applications, e.g. paving, tubes, pavers, refractories. Techniques for the mass production of alkali-activated binders have been suggested, and a first industrial plant has been built in Australia.

Up to "90%" CO_2 emission reduction compared to Portland cement is postulated. However, this does not take into account emissions due to the production of the activators (e.g. sodium silicate). In comparisons between Portland cement concrete and geopolymer concretes with an equal performance, geopolymer concretes are mostly more expensive and exhibit mostly a significantly higher resource depletion potential, a higher cumulative energy demand and a lower global warming potential. Thus, the use of available blended cements in common concrete applications seems to be more convenient for environmental and economic reasons. Based on today's knowledge, the reduction potential of materials like GBFS or fly ash used as a clinker substitute in blended cements seems to be more efficient than the use for alkali-activated binders.

Impact on energy efficiency

thermal:
reduction potential depends strongly
on energy demand for activator production
[MJ/t cem]

electric:
reduction potential depends strongly on
energy demand for activator production
[kWh/t cem]

CO_2 reduction potential

direct:
reduction potential depends strongly on CO_2
emission from activator production
[kg CO_2/t cem]

indirect:
reduction potential depends strongly on CO_2
emission from activator production
[kg CO_2/t cem]

Material input

pozzolanic or latent hydraulic materials (e.g. fly ash, ground granulated blast furnace slag)
alkalis (e.g. sodium silicates, sodium hydroxide)

not available [t/t cem]

The main influencing parameters are

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

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: Currently no real cost figures are available. They will strongly depend on the availability and processing of starting materials, costs for alkaline activators and the development of applications of alkali-activated systems.

Conditions, barriers, constraints

- Properties of alkali-activated binders strongly depend on the starting material properties, so the quality control will be an overriding problem in practice.
- The durability of the concrete has yet to be demonstrated.
- No valid test methods available.
- Availability of all components, like fly ash and slag depends on the future of coal-fired power plants and iron production.
- Operational safety during working with highly alkaline conditions
- Production quantities and costs for the alkaline activator (e.g. sodium silicate).

3.39 Technology Paper No. 39: Cements based on carbonation of calciumsilicates

One of the most globally abundant raw materials for the manufacture of hydraulic binders is limestone (calcium carbonate). Aluminates in cement react with calcium carbonate to calcium carboaluminate hydrates classified as AFm phases. In Portland cement clinker based cements less than 10% calcium carbonate can react in this way.

The carbonation mechanisms of e.g. calcium hydroxide and calcium silicates in concrete are well known from the perspective of protection against reinforcement corrosion. However, the carbonation of Ca-/Mg-silicates can also be considered as a possible CO_2 sequestration process, whereby the carbonation of Ca-silicates (e.g. wollastonite, $CaO \times SiO_2$) proceeds much more rapidly. The mechanisms of aqueous wollastonite carbonation have been observed to occur via two steps: (1) Ca leaching from the $CaSiO_3$ matrix and (2) $CaCO_3$ nucleation and growth. During the carbonation process the compressive strength rises as a function of time and CO_2–pressure (degree of reaction). Mortar strengths of up to 100 MPa are possible.

First industrial trials to produce low-lime cements composed of wollastonite / pseudo-wollastonite ($CaO \times SiO_2$) and rankinite ($3\ CaO \times 2\ SiO_2$) in rotary kilns at about 1200 °C have been conducted. During the production of such low-lime cement (e.g. Solidia Cement) up to 30% less CO_2 emissions in comparison to Portland cement are postulated. For the reference scenario of this paper no reduction has been included. This non-hydraulic cement is used for Solidia Concrete which is composed of the same raw materials and can be processed as ordinary Portland cement concrete. In contrast to strength development via hydration in common concretes, the setting and hardening characteristics of Solidia Cement are mainly derived from an exothermic reaction between CO_2 and the calcium silicates during CO_2–curing. During carbonation calcium carbonate and amorphous silica (SiO_2) is formed. The processes require a CO_2-rich atmosphere and can be conducted at ambient gas pressures and at moderate temperatures (20 to 60°C). Therefore, this technology is rather suitable for precast applications. During the curing process up to 200 to 300 kg of CO_2 per tonne of cement can be bound. The process can be stopped reaching the desired strength – typically within 24 h. It is stated that the concrete products provide at least the same properties including strength, abrasion resistance and durability as traditional concretes. It is claimed that this technology reduces the overall carbon footprint associated with the manufacture and use of cement by up to 70% in comparison to Portland cement.

Impact on energy efficiency

thermal: not available [MJ/t cem]   electric: not available [kWh/t cem]

<u>CO_2 reduction potential</u>

direct: not available [kg CO_2/t cem]   indirect: decrease of 200 to 300 [kg CO_2/t cem]

<u>Material input</u>

low calcium raw meal (limestone, quartz)   1,38 [t/t cli]

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

- Reuse/reconditioning/storage of CO_2 from clinker production
- Relative increase of use of pre-fabricated concrete products, further proof of durability
- Handling of CO_2 during manufacturing (safety at work)
- Development of corrosion-resistant reinforcements could enable use for reinforced concrete elements

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: Existing equipment for cement and concrete manufacturing can be used. Set-up of CO_2–curing systems (supply, storage, safety issues, curing chambers etc.) in precast element plants necessary.

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

- Set-up of CO_2–curing systems (supply, storage, safety issues, curing chambers etc.) in precast element plants necessary
- Reuse/reconditioning/storage of CO_2
- Extended use of pre-fabricated elements/constructions.

3.40 Technology Paper No. 40: Other low carbonate clinkers: pre-hydrated calcium silicates

Calciumhydrosilicates (CHS) can be synthesized from quartz and CaO with comparative ease by a hydrothermal process as for calcium silicate production. During subsequent heating (e.g. hillebrandite, C_2SH, heated to 500 °C) very fine and hydraulic reactive β-C_2S is formed. Furthermore, it has been found that during the heating of C_2SH, a continuous, two-stage decomposition process occurs at 390 to 490 °C during which an intermediate phase is formed. This intermediate phase exhibits extremely high hydration activity.

One current and new approach is the activation of an autoclaved non-hydraulic CHS-precursors (α-C_2SH) phase by inter-grinding with unreactive silica-rich substrates such as quartz (core-shell product). Reportedly, the α-C_2SH becomes amorphous and probably also dehydrates to some extent in a tribochemical surface reaction during inter-grinding, and thus forms a reactive coating on the substrate particles. This coating can hydrate with water leading to CSH-mediated bonding between the particles. The manufacture of the so called "Celitement" follows three steps: (1) the calcination of limestone (CaO); (2) reaction of lime, silica and water in an autoclave at about 200 °C at 12 bar to produce α-C_2SH, and (3) drying and inter-grinding of α-C_2SH with a siliceous filler such as quartz. Such binders are based on the same and very abundant raw materials as are also needed for traditional cement production. Celitement does not represent a single binder but rather an entire family of mineral binders based on calcium hydrosilicates with a wide range of composition.

The binder is reported to be compatible with conventional cements and ordinary admixtures. The hydration characteristics, the strength development and the final strength vary in the same range as conventional cements (cement standard strength up to 80 MPa). During hydration a matrix with very low permeability (without $(CaOH)_2$) is formed very early, which might be advantageous for high durability applications.

For the production of Celitement an industrial energy demand of about 3150 kJ/kg primary energy is postulated with the assumption of inter.grinding of α-C_2SH and quartz sand at 50 mass% each. Total emissions of 483 kg CO_2/t are claimed for lime-rich Celitement, which corresponds to about 57% of the emissions from clinker production. This is mainly because the binder contains a high content of a relatively inert filler such as quartz. New analytical techniques for controlling the autoclave process or characterisation of the product are still under development. There is still a large potential for optimisation, as the principles of activation grinding in vibrating tube mills are very different from the experience with "simple" comminution, e.g. ball mills or vertical mills. A first industrial-scale plant is planned for 2017/2018.

Impact on energy efficiency

thermal: not available [MJ/t cem]   electric: not available [kWh/t cem]

CO$_2$ reduction potential

direct: not available [kg CO$_2$/t cem]   indirect: not available [kg CO$_2$/t cem]

Material input

limestone, quartz   amount of material not available [t/t cem]

The main influencing parameters are

- Decrease of CO$_2$ emissions by using a precursor material with low Ca/Si ratios and of crystalline or non-crystalline silicate as the core material
- Development of measurement techniques for production and quality control
- Use of such binders in combination with classical cements – use in cementitous preparations

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: Cost estimation is not possible as the technology is still at R&D level.

Conditions, barriers, constraints

- Additional autoclave batch process, optimisation of autoclave process
- New technologies necessary for coating and activation process by inter-grinding, must be optimised and up-scaled
- Lower buffer capacity due to low calcium content can affect corrosion inhibition of reinforcement.

3.41 Technology Paper No. 41: Other low carbonate cements - Belite cements

Ordinary Portland cement (OPC) clinker is produced with LSF (lime saturation factor) between 90 and 102 and typically contains 40 to 80 mass% alite ($C_3S=Ca_3SiO_5$). In contrast, so-called belite clinker can be burnt like OPC clinker but with lower amounts of calcium (LSF down to 78 to 85) and at lower temperatures around 1350 °C. Belite clinker contains no or only small amounts of alite but up to 90 mass% belite ($C_2S=Ca_2SiO_4$). Considering greenhouse gas emissions, about 40 kg CO_2/t clinker can be saved due to the reduction of limestone demand. Since there is no alite formation required, burning temperatures just above the initial melt formation of about 1350 °C are sufficient. 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. Energy savings due to the reduced burning temperatures in the magnitude of < 10% of the total heat demand are reported, but very rapid cooling, which is technically necessary, is an economic problem. This is because the heat of the clinker cannot be recuperated with currently known equipment and the related amount of energy is lost. One further drawback is the high hardness of belite requiring extra energy for grinding.

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 be-lite compared to alite, leading to a decelerated strength development that is considered unsatisfactory by most customers. The hydraulic hardening can be improved by the addition of OPC. Furthermore, the stabilisation of belite and an increase of its hydraulic reactivity can be achieved by thermal treatment (rapid cooling rate) and by incorporating foreign elements (such as K, Na, S, B, Fe, Cr and Ba). Increased alkali contents are a severe disadvantage in concrete technology.

For the hydration of belite less water is needed in comparison to alite. Thus, the water/cement ratios in belite cements can be lowered and the pore structure of hardened concrete can be remarkably improved, leading to increased long term strength and durability. The moderate development of hydration heat makes belite cement suitable particularly for massive concrete structures.

Impact on energy efficiency

thermal: decrease of 150 to 200 [MJ/t cli]   electric: increase of 20 to 40 [kWh/t cem]

<u>CO$_2$ reduction potential</u>

direct: decrease of 13 to 17 [kg CO$_2$/t cem]   indirect: increase of 10 to 20 [kg CO$_2$/t cem]

<u>Material input</u>

as for conventional Portland cement   nearly same amount (1.51) [t/t cli]

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

- 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 demand for grinding to achieve a higher cement fineness
- Grindability of belite-rich clinker
- CO$_2$ intensity of fuel use
- CO$_2$ intensity of electricity consumption

<u>Cost estimation</u>

Cost estima-tion	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	similar to standard cement plants	not available	0 to 12	increase 2.0 to 3.8
2030	similar to standard cement plants	not available	0 to 12	increase 2.4 to 4.5
2050	similar to standard cement plants	not available	0 to 12	increase 2.8 to 5.3

Remarks:

- For the improvement of the early strength of belite cements installations for clinker quenching 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 alternative raw materials, possibly increased electricity costs for grinding of alternative raw material and cement of higher fineness
- The costs for the industrial production of belite clinkers by sol-gel or hydrothermal processes cannot be estimated today because these technologies are still on laboratory-scale

Conditions, barriers, constraints

- Poor early strength development of belite cements
- Market acceptance
- Rapid cooling of belite clinker eliminates efficient heat recuperation
- High alkali contents of the clinker.

3.42 Technology Paper No. 42: Other low carbonate clinkers: (belite) calcium sulfoaluminate clinker

Many types of calcium sulfoaluminate-based cements (CSA) have been developed, especially in China, since the 1970s. Initially they were intended for the manufacturing of self-stress concrete pipes due to their swelling properties. Calcium sulfoaluminate cements mainly contain the phases ye'elimite or tetracalcium trialuminate sulfate ($C_4A_3\$$), belite (C_2S) and gypsum as well as other phases like C_4AF, mayenite $C_{12}A_7$, C_3A and C_6AF_2. According to the amount of added gypsum, a series of cements ranging from rapid-hardening to expansive can be produced. When CSA cement hydrates, mainly ettringite is formed. The overall annual CSA cement production is estimated to be around 2 Mio. t with the vast majority being produced and used in China.

Some approaches being investigated by cement manufactures are to combine the advantages of belite cements (see Technology paper 41) and calcium sulfoaluminate cements. Such intermediate clinkers (BCSA - belite calcium sulfoaluminate clinker) can contain belite, calcium sulfoaluminate (ye'elimite, $C_4A_3\$$), calcium aluminoferrites (C_4AF, C_2F), ternesite ($C_5S_2\$$) as principal phases and also includes certain combinations of minor elements in order to stabilise the belite in the more reactive α' form. During hydration ettringite and aluminium hydroxide (AH_3) (early strength) as well as CASH-phases (later strength) and monophases are formed.

With BCSA, clinker cements with similar performance to Portland cements (OPCs) can be produced in conventional Portland cement plants at 150 to 200 °C lower sintering temperatures and with 20 to 30% less CO_2 emissions than equivalent OPCs. BCSA clinkers are more friable and therefore easier to grind. Thus, 30 up to 50% less grinding energy compared to OPC is required. For the stabilisation of ternesite a longer pre-cooling period of the clinker is required.

Strength development and concrete durability depend on the composition of BCSA cements. Concretes usually show a high sulfate resistance but often less carbonation and chloride migration resistance. At present such cements are commercially available in Europe and can be applied according to technical approvals. The use of higher amounts of bauxite and sulfate as raw material makes these cements expensive. Other cements like the so-called Porsal cement are also produced with reduced lime contents but higher contents of alumina up to 15 mass% and minor amounts of SO_3. Porsal cement is also a kind of BCSA cement burned with CaF_2 as mineralizer.

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 $C_4A_3\$$ and internal recirculating sulfate systems in the kiln.

Impact on energy efficiency

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

CO_2 reduction potential

direct: not available [kg CO_2/t cli]   indirect: not available [kg CO_2/t cli]

Material input

limestone, bauxite, sulfates, quartz   amount not available,
                                                    individual compositions [t/t cli]

The main influencing parameters are

- Availability and costs of alumina and sulfate sources
- Low alkalinity could affect corrosion protection of reinforcement
- Proof of concrete durability
- Cement composition can be varied in wide range

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: The variety of individual compositions, characteristics of the production process and products do not allow for a consistent quantitative assessement.

Conditions, barriers, constraints

- Higher costs and limited availability of alumina and sulfate sources
- Lack of experience regarding construction concretes
- Lack of standards and regulations
- Market acceptance.

3.43 Technology Paper No. 43: Oxyfuel Technology

Oxyfuel technology relies on the use of oxygen for combustion instead of ambient air. This requires an air separation unit (ASU) to provide the oxidizer by removing the nitrogen which is state-of-the-art. 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. Thus, the carbon dioxide concentration in the flue gas increases significantly up to above 80%. This would have a huge impact on the clinker burning process, mainly on the energy balance and the ratio between the enthalpy flow of the kiln gas and the energy needed for the chemical/mineralogical reactions of the kiln feed. Apart from the temperature profile optimal for clinker phase formation, the optimum oxygen level significantly depends on the design of the kiln plant and therefore the implementation option: retrofit or new installation. 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. Besides the air separation, the purification step is responsible for a significant increase in electrical energy demand. The achievable CO_2 concentration in the discharged flue gas as a major influencing factor strongly depends on the level of false air leaking into the system. Although false air could be reduced to a tolerable level by improved maintenance of the kiln plant, this is still a critical issue for the application of oxyfuel processes. As 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 today.

Two options for the application of oxyfuel technology have been developed: The full application includes the whole kiln plant and therefore requires also the adaptation of the kiln and cooler. In this way capture rates of 90 to 99% could be achieved. The partial approach includes only the calciner. Whereas this application only requires the redesign of the equipment involved, the capture rate is limited to 55 to 75%. Both application options require a sophisticated heat recovery system due to the recirculation of flue gases and the necessary minimisation of false air. In this way the common waste heat utilisation, e.g. for raw material drying, is limited (full oxyfuel mode to raw material moisture content <6%) in order to avoid additional firing and therefore unabated CO_2 emissions.

In the past years much lab-based and simulation-assisted research with regard to operation, clinker quality and equipment re-design has been done on oxyfuel technology in the cement industry. On this basis prototype testing is planned, but larger-scale demonstration as the next step towards commercialisation is still lacking. A first demonstration of oxyfuel technology is not planned before 2020, thus the operation of a first-of-its-kind commercial-scale plant is not expected before 2025. For 2050 several roadmaps predict that a significant number of cement plants will be equipped with carbon capture technologies to meet a CO_2 reduction from those technologies by 50 to 60%

Impact on energy efficiency

thermal: decrease of 200 to increase of 250 [MJ/t cli]

electric: increase of 117 to 180 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 530 to 835 [kg CO_2/t cli]

indirect: increase of 60 to 90 [kg CO_2/t cli]

Material input

Oxygen   0.25 to 0.3 [t/t cli]

The main influencing parameters are

- Achievable CO_2 concentration in the flue gas and required CO_2 purity in the final CO_2 stream for storage/reuse
- Level of air in-leaks
- Separation ratio of the CO_2 purification
- Energy demand of the CO_2 separation, purification and compression facility and the air separation unit
- Oxidiser purity (influences energy demand)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	not available	not available	not available	not available
2030	355 to 380	8 to 13 increase	105 to 130	9 to 14 increase
2050	290 to 312	9 to 15 increase	86 to 107	10.5 to 16.5 increase

Remarks: The cost estimation is based on a designed clinker capacity of 2 Mio. t/a, with no inflation. Investment costs include oxygen supply and CO_2 purification and compression. Costs for CO_2 transport and storage are excluded. Basically, a huge uncertainty regarding the cost estimation exists, resulting from the still incomplete development of the technology.

It is assumed that a first demonstration plant could come into operation in 2020 at significant-ly higher costs than described above. A learning rate of 1% per year is considered for the pe-

riod 2030 to 2050. Operational costs are expressed as additional costs compared to a conventional kiln and include mainly additional power costs. Depreciation, interest and inflation are not included in operational costs.

Conditions, barriers, constraints

- Technology is still not proven in demo-scale in 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
- Availability of transport (pipeline) grid and operated storage sites or reuse options
- Electric energy demand per ton of clinker will increase by a factor of 2 to 3 ("energy or CO_2 penalty")
- Production costs will increase by 40 to 50% related to current cement production costs (threat of carbon leakage).

3.44 Technology Paper No. 44: Post-combustion capture using absorption technologies

Absorption techniques are discussed as an end of the pipe measure for CO_2 abatement. Along the whole exhaust gas path of a cement plant, the flue gas is diluted by the infiltration of air. As a result of this, the CO_2 concentration decreases from above 30% at the preheater exit to about 20% or below in the stack.

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 for transport to a designated destination (storage site or reuse facility). The chemical absorption with alkanolamines is a proven technique in other industry sectors like the chemical or gas industry. As flue gas volumes and absorbent cycles are significantly smaller in these industries 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. Advanced amines are commercially available granting lower energy demand 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 to these issues and is currently being investigated for an application at the clinker burning process in a European research project.

Due to high costs 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 can also lead to solvent degradation. On the other hand, the share of NO_2 is only 5 to 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 for the regeneration process can be recovered from the 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 a significant manner, but allows smaller absorber structures due to less gas volume flow.

Many pilot projects about CO_2 capture with absorption technologies have been carried out in the power sector. An industrial-scale CO_2 capture project is being carried out at SaskPower's Boundary Dam power plant in Canada. Furthermore, a first pilot project has also been carried out in the cement industry. Aker Solutions has conducted trials with a mobile test unit from 2013 to 2016 in the Brevik cement plant in Norway. An amine-based sorbent was

successfully tested to capture CO_2 from a small side stream of the cement plant's flue gas. Around 8,000 h of operational experiences have been gained. The total CO_2 capture of the mobile test unit amounts to 2,000 t/yr.

Another project on a larger scale is the SkyMine Project which is being carried out in the Capitol cement plant in San Antonio (USA). The SkyMine project can also be classified as a CCU project as the reaction product of the absorption process and other co-generated products can be sold. In the SkyMine process the CO_2 containing flue gas reacts with sodium hydroxide to produce sodium bicarbonate ($NaHCO_3$). The NaOH solution is produced on site with a chloralkali electrolysis. Hydrogen and chlorine are generated as co-products and are used to produce HCl and sodium hypochlorite (NaClO; bleach). The products $NaHCO_3$, HCl and NaClO can be marketed, so that the whole plant can be operated with a profit. When running at full capacity, the SkyMine plant could capture 75,000 t CO_2/yr.

Impact on energy efficiency

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

CO_2 reduction potential

direct: decrease of 0 to 740 [kg CO_2/t cli]   indirect: increase of 25 to 60 [kg CO_2/t cli]

Material input

replacement of absorbent   0.001 – 0.004 [t/t cli]

The main influencing parameters are

- Type of absorption process
- Available heat, low pressure steam, shaft work (supplied from co-located power plant)
- Sour gas loading (SO_2, NO_2)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
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 for the installation of a power-to-gas plant are the same for both the installation in an existing cement plant and in a new cement plant.

Conditions, barriers, constraints

- Overall primary energy demand 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 knowledge on absorption technologies
- Availability of transport (pipeline) grid and operated storage sites
- Huge additional energy demand ("energy or CO_2 penalty")
- Extremely high costs compared to cement production costs.

3.45 Technology Paper No. 45: Post-combustion capture using membrane processes

Membranes are being discussed as a future end-of-the-pipe measure for CO_2 abatement. In principle, more than 80% of CO_2 can be captured with this technique. After abatement, the CO_2 has to be purified and compressed for transport to designated storage sites or reuse facilities. Up to now, such membranes have only been available on a very small or research scale. Further development is expected to need about 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 could be needed 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, namely gas separation membranes (gas / gas membranes) and gas absorption membranes (gas / liquid membranes). A further development could be a hybrid capture system consisting of a membrane separation process combined with a chemical absorption process like amine scrubbing.

Gas / gas membranes rely 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 on 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 for example in offshore and remote locations.

However, membranes also show unfavourable characteristics like sensitivity to sulphur compounds and other trace elements, and sometimes low degrees of separation (multiple stages or recycling is necessary), and polymeric membranes are mostly intolerant against high temperatures.

First trials, more or less on laboratory scale, have been carried out with flue gas from a cement kiln. A one-stage membrane module with a polyvinyl-based flat sheet membrane was investigated in a six-month test programme. A CO_2 recovery rate of 60 to 70% could be achieved. The results show that the membrane material could withstand the flue gas from the cement kiln.

Impact on energy efficiency

thermal: not available [MJ/t cli]   electric: increase of up to 300 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 700 to 760 [kg CO_2/t cli]   indirect: increase of up to 195 [kg CO_2/t cli]

Material input

not applicable   not applicable [t/t cli]

The main influencing parameters are

- Operating conditions
- Membrane properties, selectivity
- Separation performance

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2015	45 to 60	increase 15 to 25*	not available	not available
2030	not available	not available	not available	not available
2050	not available	not available	not available	not available

* compression up to 80 bar is included; the membrane selectivity affects the operational costs significantly

Remarks: Membrane technologies are in a very early development stage so that reliable cost estimations are not available. According to a benchmark study, which was carried out for the small-scale carbon capture project in a Norwegian cement plant, the total costs for CO_2 cap-

ture with membrane technologies could range between 43 €/t cli. and 63 €/t cli. (depending on coal and electricity prices), which corresponds to former data in technical literature. Cost information published by the UNESCO Centre for Membrane Science and Technology a couple of years ago which predicted specific costs of 45 to 50 €/t CO_2 avoided for 2015 and lower costs < 25 €/t CO_2 avoided for 2030 and 2050 is still realistic.

Conditions, barriers, constraints

- High operating pressures (separation membranes) required
- Separation efficiency and temperature resistance has to be improved
- Scale-up to full-size implementation required
- Availability of transport (pipeline) grid and operated storage sites
- Very high costs compared to cement production costs.

3.46 Technology Paper No. 46: Post-combustion capture using solid sorbents: Ca looping

The so-called calcium looping (CaL; also called carbonate looping) process is based on the equilibrium of calcium carbonate to calcium oxide and carbon dioxide at different 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 exothermic carbonation could take place at temperatures between 600 and 700 °C in a so-called carbonator. The energy from the carbonation reaction – due to the high gas temperature – can be used for electricity generation.

The produced calcium carbonate is directed to a calciner for regeneration of the sorbent in an endothermic reaction at temperatures above 900 °C. For a gas stream rich in carbon dioxide the calciner has to be fired with pure oxygen (oxyfuel combustion). Both the carbonator and the calciner are fluidised beds which provide a good contact between the gas streams and the solids. Additional equipment like cyclones is needed to separate the solids from the gas streams.

The gas stream coming out from the calciner shows a high CO_2 concentration of up to 95 % and (after a further purification and compression) is supplied for subsequent storage or utilization. The recycled adsorbent is transferred back to the carbonator and maintained in a cycle. Due to deactivation processes, a make-up of the adsorbent is required. The CaO-rich purge stream could be utilised as alternative raw material for the clinker burning process. This would result in beneficial reductions of the fuel consumption and the CO_2 emissions.

The calcium looping process can be applied to power plants, cement plants and other industrial CO_2 sources. It has been investigated in different lab-scale plants, e.g. at IFK in Stuttgart, INCAR-CSIC and La Pereda in Spain, at TU Darmstadt and CANMET. Taiwan Cement and the Industrial Technology Research Institute (ITRI) started a calcium looping pilot project in 2013 which exhibits a capture rate of 1 t CO_2/h.

An advanced variant for cement plants would be an integrated process where the CaL system substitutes the conventional precalciner as has been developed e.g. by Polytecnico di Milano in cooperation with a cement producer. A certain amount of CaO is diverted to the carbonator reactor where it reacts with the CO_2 generated in the rotary kiln. The remaining proportion of CaO is fed into the rotary kiln. The $CaCO_3$, which is generated in the carbonator, is directed to the calciner where the CO_2 is released in a concentrated gas stream. After a final purification, the CO_2 can be transported to a storage site or to a reuse facility.

Impact on energy efficiency

thermal: increase of 700 to 1,400 [MJ/t cli]   electric: not available [kWh/t cli]

The oxyfuel fired calciner, where the endothermic calcination takes places, has a high heat demand. Energy released in the exothermic carbonation reaction can be used for the generation of electricity. On the other hand, the air separation unit for the O_2 production (oxyfuel fired calciner) has a high electricity demand. In total, the power produced by the steam cycle could be in the same magnitude as the power demand of the cement plant so that the plant could be power self-supplied.

<u>CO_2 reduction potential</u>

direct: decrease of 760 to 800 [kg CO_2 /t cli]   indirect: not available [kg CO_2 /t cli]

<u>Material input</u>

Make-up limestone	ca. 0.8 [t/t cli]
Oxygen	0.06 [t/t cli]

A cement plant with a clinker capacity of 3,000 t/d would require a make-up stream of around 30 kg/s which is equivalent to > 100 t/h.

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

- Type of sorbent
- Options to utilise the purge stream

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: The Ca looping process for CO_2 capture is still in an early stage of development and has not reached commercial status for CO_2 recovery from flue gases. Therefore, no detailed cost data have been published up to now. Nevertheless, there are cost estimations about the specific costs for an application at the clinker burning process, which range from 20 to 40 €/t CO_2. In accordance with these data, an economic analysis for the capture project

in a Norwegian cement plant resulted in a cost estimation of 36 €/t cli. The investment costs for a CaL installation could be up to 180 to 200 Mio. €.

Conditions, barriers, constraints

- Still in the stage of research and development
- Sorbent deactivation
- High mass streams have to be handled
- Make-up of sorbent required (deactivated CaO can be utilised in the clinker burning process).

3.47 Technology Paper No. 47: Post-combustion capture using solid sorbents: Mineral carbonation

Mineral carbonation is a chemical process in which magnesium and calcium silicates (e.g. serpentine, olivine, wollastonite) are reacted with CO_2 to form stable carbonates. The required alkalinity is provided by natural alkaline minerals (e.g. magnesium- and calcium-rich silicates) which are widely available worldwide. Industrial wastes (fly ash, cement kiln dust, blastfurnace slag) instead of natural minerals can also be used as starting materials. An advantage of this capture process is the fact that it is not required to use pure CO_2 for the mineral carbonation. The final output is inert carbonates which can be used e.g. as construction materials or which can be stored for long periods without risk of CO_2 leakage. As a result of this, mineral carbonation includes both the capture of CO_2 and its long-term storage. Mineral carbonation can be carried out as a single or multi-step process. In the single-step process a direct carbonation takes place under high pressures without or with (mechanical, thermal) pretreatment. The objective of the pretreatment is to accelerate the carbonation reaction by an increase of the surface area. The reaction is possible both in dry or aqueous media. The involved reactions are similar to naturally occuring processes which are called "wheatering".

In contrast to this, the multi-step or indirect carbonation involves the extraction of the reactive metal ions from minerals using acids or other solvents followed by the carbonation reaction in the gaseous or aqueous phase. The indirect carbonation can be divided into different steps:
- separating of the metal from the mineral mix, e.g. in the presence of HCl or a molten salt
- a series of hydration reactions to obtain the metal hydroxide
- carbonation reaction (carried out at elevated temperature and pressure).

A disadvantage of the process is the slow reaction rates of carbonation. However, there are different possibilities to enhance the reduction rate, e.g. elevated temperature and pressure, chemical processing and mechanical treatment (grinding). The results obtained with the mineral carbonation show that industrial wastes are more reactive so that the chemical reactions can be carried out under mild conditions.

The mineral carbonation technology is still in the R&D phase and up to now no large-scale adsorption units are known for CO_2 capture from flue gases. The required mineral mass to bind 1 t of CO_2 is between 1.8 and 3 t for relatively pure minerals. According to this, huge mining activities would be required to capture the CO_2 from power plants or cement plants. According to the literature, the requirement of thermal energy is around 3 GJ/t CO_2, which corresponds to 2.55 GJ/t cli. Additional electrical energy is needed for crushing and grinding processes and for gas compression.

Impact on energy efficiency

thermal: increase of 2,550 [MJ/t cli]   electric: increase of 300 to 700 [kWh/t cli]

CO_2 reduction potential

direct: decrease of 750 [kg CO_2/t cli]   indirect: not available [kg CO_2 /t cli]

Material input

Ca or Mg silicates   1.5 to 2.5 or more [t/t cli]

The main influencing parameters are

- Type of process (direct /indirect carbonation)
- Type of feedstock
- Pretreatment of the minerals

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: Cost estimations for the mineral carbonation process have been published recently in technical literature. According to this, the total cost of in-situ mineral carbonation could range from 65 to 117 €/t CO_2. For ex-situ mineral carbonation the cost estimations range from 41 to 173 €/t CO_2, depending on the type of feedstock.

Conditions, barriers, constraints

- Large material transport and storage requirements
- High energy demand for the mining, transportation and preparation of the mineral; through this the CO_2 removal efficiency is significantly reduced
- Slow reaction rate of carbonation
- Limiting factor: availability of alkalinity
- Very high costs compared to geological storage.

### 3.48 Technology Paper No. 48: CO$_2$ use: Basic chemicals, urea, formic acid, polymers

CO$_2$ captured from the flue gases of industrial emittors can be used as feedstock for the synthesis of chemicals or special polymers. In principal there are many possibilities for synthesizing organic molecules from CO$_2$. However, the utilisation of CO$_2$ for chemical syntheses needs efficient catalytic systems in mosts cases. In this connection, the hydrogenation of CO$_2$ is an important possibility for the chemical conversion of CO$_2$.

Urea (CO(NH$_2$)$_2$) is the most important product for which CO$_2$ is used as a C1 building block. It is produced from CO$_2$ and NH$_3$ under high pressure and temperature:

$$CO_2 \quad + \quad 2\,NH_3 \quad \rightarrow \quad CO(NH_2)_2 \quad + \quad H_2O$$
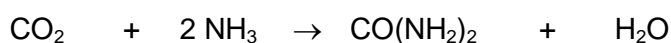
In most cases, the urea production is carried out in the vicinity of ammonia plants as large amounts of CO$_2$ are generated in the syngas production for the ammonia synthesis. Most of the produced urea is used as agricultural fertiliser.

Formic acid is another basic chemical which can be produced by a selective hydrogenation of CO$_2$:

$$CO_2 \quad + \quad H_2 \quad \rightarrow \quad HCO_2H$$
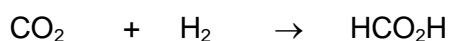
However, the catalytic hydrogenation for the production of formic acid is not yet an established process and cannot compete with the standard production process (reaction between methanol and CO in the presence of a strong base; subsequent hydrolysis reaction). Formic acid and its salts are used in different industrial applications, e.g. in the leather industry, as a de-icing agent or as preservatives.

Furthermore, polymers like polycarbonates and polyurethanes can make use of captured CO$_2$ as an alternative carbon source. For example, polycarbonates can be produced by a reaction between CO$_2$ and epoxides. Polyols, which are a starting material for polyurethane production, can also make use of captured CO$_2$ from flue gas streams. A first industrial-scale production line has recently been built in Germany.

To meet the required global CO$_2$ reduction targets for climate protection, huge amounts of CO$_2$ have to be stored or reused. It is evident that the potential for the production of chemicals and polymers from captured CO$_2$ is limited – taking into account the current world market for the respective products. However, the motivation of chemical companies for the reuse of captured CO$_2$ is to achieve sustainable production and to broaden their raw material base.

Impact on energy efficiency

thermal: not applicable [MJ/t cli]   electric: not applicable [kWh/t cli]

The further utilisation of captured CO_2 for the production of basic chemicals does not affect the energy demand of the actual clinker burning process.

CO_2 reduction potential

direct: not applicable [kg CO_2/t cli]   indirect: not applicable [kg CO_2/t cli]

Material input

not applicable   not applicable [t/t cli]

The main influencing parameters are

- Purity of the CO_2 gas stream
- Added value related to required product

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: The reuse of CO_2 for the production of basic chemicals is still in a very early stage of development. Reliable data on the costs are not yet available.

Conditions, barriers, constraints

- Limited markets
- Competition with traditional production routes.

### 3.49 Technology Paper No. 49: CO$_2$ use: Power-to-gas (CH$_4$)

The further destination of captured CO$_2$ is an important issue for all CO$_2$ reduction projects. The long-term storage of CO$_2$ in underground geological formations is still the option which could offer a potential for billions of tonnes of CO$_2$. However, the public acceptance for CO$_2$ storage is low in many countries so the reuse of CO$_2$ is also being investigated as an option for the captured CO$_2$.

The reuse of CO$_2$ for CH$_4$ production is an important option for energy storage concepts. The required hydrogen could be produced with excess electrical energy from renewable sources (wind, solar). The produced methane could be stored in the existing grids for natural gas which offer a huge storage capacity. Against this background, the power-to-gas concept is also an interesting option for energy storage.

According to this, a power-to-gas project consists of the following main process steps:
- the capture of CO$_2$ from flue gases of power plants, cement kilns or other industrial sources
- the production of hydrogen by water electrolysis using renewable electrical energy
- the catalytic conversion of CO$_2$ with hydrogen to form methane

For the capture of CO$_2$ chemical absorption technologies based on amines (e.g. MEA, see TP 44) would be the most developed process. The CO$_2$ gas stream should exhibit a sufficient purity for the subsequent catalytic reactions. Possible technologies for the hydrogen production are the alkaline electrolysis, the PEM electrolysis and the solid oxide electrolysis (SOEC). The hydrogen production by water electrolysis requires a huge demand of electrical energy. Methane is produced with the so-called Sabatier reaction, an exothermic catalytic reaction between CO$_2$ and hydrogen in the presence of transition metal catalysts (mostly Ni catalysts):

$$CO_2 \quad + \quad 4\,H_2 \quad \rightarrow \quad CH_4 \quad + \quad 2\,H_2O$$
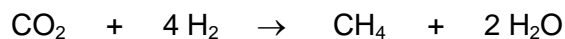
The whole process needs a very high amount of electrical energy for the hydrogen production.

In different countries pilot trials are being carried out, utilising CO$_2$ from different sources. However, there are no operational experiences from industrial-scale projects, neither in the cement industry nor in the power sector. Up to now, the economic feasibility is not given, as the costs for natural gas are significantly lower than the costs for CH$_4$ from catalytic methanation.

Impact on energy efficiency

thermal: not applicable [MJ/t cli]   electric: not applicable [kWh/t cli]

The further utilisation of captured CO_2 for PtG projects does not affect the energy demand of the clinker burning process. However, the energy demand of the applied capture technology has to be taken into account.

CO_2 reduction potential

direct: not applicable [kg CO_2/t cli]   indirect: not applicable [kg CO_2/t cli]

Material input

not applicable   not applicable [t/t cli]

The main influencing parameters are

- Costs for electrical energy from renewable sources
- Taxes and duties on the electrical energy
- Purity of the CO_2 gas stream

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: A first feasibility study for a PtG project has been carried out in the German cement industry. According to this, the CAPEX for a PtG plant (consisting of a 50 MW water electrolysis with a H_2 production of 10,000 Nm^3/h, an amine scrubber with a capture rate of 117 t CO_2/h and a CH_4 production of 42.9 t/d) would amount to 76 Mio € and an OPEX of 12.3 Mio €/a. The overall assessment showed that the economic feasibility is not given under the current economic framework conditions.

Conditions, barriers, constraints

- Electricity prices
- Natural gas prices
- No incentives for the production of renewable methane.

3.50   Technology Paper No. 50: CO$_2$ use: Power-to-liquids (CH$_3$OH)

The further destination of captured CO$_2$ is an important issue for all CO$_2$ reduction projects. The long-term storage of CO$_2$ in underground geological formations is still the option which could offer a potential for billions of tonnes of CO$_2$. However, the public acceptance for CO$_2$ storage is low in many countries so the reuse of CO$_2$ is also being investigated as an option for the captured CO$_2$. A potential reuse option, which is called the power-to-liquids (PtL) process, is the conversion of electrical energy from renewable sources into fuels or methanol. By this, the electricity grid can also be stabilized, especially in phases when excessive electricity supply is available.

A power-to-liquids project consists of the following main process steps:
-    The capture of CO$_2$ from flue gases of power plants or other industrial sources
-    The production of hydrogen by water electrolysis using renewable electrical energy
-    The catalytic conversion of CO$_2$ with hydrogen to form methanol or fuels

Renewable methanol can be produced according to the following chemical reaction:

$$CO_2 \quad + \quad 3\,H_2 \quad \rightarrow \quad CH_3OH \quad + \quad H_2O$$
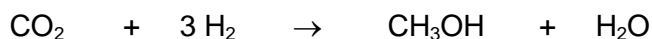
The captured CO$_2$ should exhibit a sufficient purity for the subsequent catalytic reactions. The currently biggest production of renewable methanol is located in Iceland, where a company operates a plant with a capacity of around 4,000 t/a. The plant uses geothermal power to produce the required hydrogen and utilises CO$_2$ captured from a nearby geothermal power plant to produce a CO$_2$ rich syngas.

Methanol is a basic chemical compound which can be used for a variety of chemical conversions to other products or which also can be used as a fuel. In some countries, gasoline is blended with small percentages of methanol. Similar to the power-to-gas concept, power-to-liquids is also an interesting option for energy storage.

Another option for the power-to-liquids process is the catalytic conversion of CO$_2$ and renewable hydrogen to fuels:

$$CO_2 \quad + \quad 3\,H_2 \quad \rightarrow \quad \text{-CH}_2\text{-} \quad + \quad 2\,H_2O$$
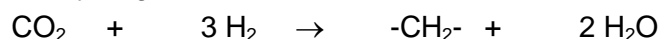
A German start-up company has built a demonstration rig which can produce up to one barrel of fuels per day (petrol, diesel, kerosene). However, the economical feasibility is not yet given.

Impact on energy efficiency

thermal: not applicable [MJ/t cli]   electric: not applicable [kWh/t cli]

The further utilisation of captured CO_2 for PtL projects does not affect the energy demand of the clinker burning process. However, the energy demand of the applied capture technology has to be taken into account.

CO₂ reduction potential

CO_2 reduction potential

direct: not applicable [kg CO_2/t cli]   indirect: not applicable [kg CO_2/t cli]

Material input

not applicable [t/t cli]

The main influencing parameters are

- The costs for electrical energy from renewable sources
- Taxes and duties on the electrical energy

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: The costs for the installation of a power-to-liquids plant are the same for both the installation in an existing cement plant or in a new cement plant.

Conditions, barriers, constraints

- Competitive market with methanol or fuels from traditional production processes
- No incentives for the production of renewable methanol or fuels.

3.51 Technology Paper No. 51: CO$_2$ use: Enhanced Oil Recovery (EOR)

Enhanced oil recovery (EOR) is the general term for various techniques which can be applied to increase the recovery of oil in depleted or high viscosity oil fields. One of these possibilities is to inject CO$_2$ to boost the oil production. Through this, CO$_2$ injection has the potential not only to increase the yield of an oil field but also to store captured CO$_2$ from CCS projects. In contrast to other utilisation routes for CO$_2$, there is already a market for CO$_2$ EOR and profits can be achieved for the supply of CO$_2$ to oil producers.

Around 5 to 40% of the oil in a reservoir can be produced with so-called primary production (natural reservoir drives are used to recover the oil) and an additional 10 to 20% with secondary production, which would include water flooding of the reservoir. The primary and secondary production targets mobile oil in a reservoire. EOR technologies (also known as tertiary recovery) are applied to further improve the recovery factor of an oil field, so that an additional 7 to 23% can be produced, which otherwise are inaccessible (immobile oil).

EOR technologies include the injection of different agents into the reservoir to extract immobile reserves of oil. CO$_2$ can be used, but also steam, chemicals or polymers. In the case of CO$_2$, most of the injected CO$_2$ returns back to the surface with the pumped oil where it has to be recycled for another injection process. At the end of the oil recovery the injected CO$_2$ has to be retained in underground storage. In this case, more requirements have to be met, e.g. a minimum reservoir depth.

EOR is a mature technology and has been used in many oil fields worldwide, mostly in the USA and in Canada. Up to now, most of the CO$_2$ for EOR projects has been provided from naturally-occuring underground reservoirs. However, today captured CO$_2$ from industrial sources (e.g. from the power sector, cement or steel industry) can also be utilised to boost oil production. Up to now, there are no implemented projects using captured CO$_2$ from cement plants for an EOR application.

Long-term experiences are have been available for more than 40 years from different projects, e.g. from the Weyburn Project (Saskatchawan/Canada), where 8,500 t/d have been injected into a depleted oil field. In this case, each tonne of injected CO$_2$ increased the oil production by 2 to 3 barrels.

The further utilisation of captured CO$_2$ for EOR does not affect the energy demand of the clinker burning process. However, the energy demand of the applied capture technology has to be taken into account.

Impact on energy efficiency

thermal: not applicable [MJ/t cli]   electric: not applicable [kWh/t cli]

<u>CO_2 reduction potential</u>

direct: not applicable [kg CO_2 /t cli]   indirect: not applicable [kg CO_2 /t cli]

<u>Material input</u>

not applicable   not applicable [t/t cli]

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

-   Pipeline specifications (CO_2 purity)
-   Competitive market with CO_2 from natural sources

<u>Cost estimation</u>

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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: The CO_2 supply price is dependent on the current oil price and has varied between 9 and 27 €/t CO_2 in the past 30 years. It is expected that an EOR operator will be paid by a CO_2 supplier in the future if a climate target of less than 2 °C global warming is achieved.

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

-   Various local requirements, e.g. oil reservoirs, CO_2 sources, transport infrastructure etc.

3.52 Technology Paper No. 52: CO_2 use: Algae capture and fuel production, biofuels

The mitigation of CO_2 via photosynthesis is an option to produce alternative fuels or so-called biofuels or fish and animal feed. CO_2 containing flue gas streams from power plants or cement plants can be used as a source for microalgae cultivation. Microalgae are water-based organisms which grow in fresh, saline or brakish seawater or wastewater. They grow with photosynthesis and their development requires light, CO_2, water and some mineral salts. Microalgae differ in shape, size, chemical structure, composition and colour, and can be classified in different categories. The microalgae can be grown in open systems (unstirred or stirred ponds) or closed systems (tubular or flat panel reactors). Productivity can be increased by fertilizers.

The produced algae can be harvested, dried and used as a renewable fuel to replace coal in different applications. Another option is the further processing into 3rd generation biofuels, animal feed, proteins, lipids, antioxidants, etc., which have higher market value. Biogas is a by-product of the process, which can be used for supplying heat or electricity back into the process. Biomass remaining after fuel extraction can be used for the production of chemicals or animal feed. For biofuel production it is important that the required energy for all process steps is sourced from renewables, otherwise the process would be associated with additional CO_2 emissions. The space requirement for an algae project is extremely high: a so-called BAT cement kiln with an annual clinker production of 1 Mio. t/yr would have a space requirement for the algal cultures between 40 and 70 km^2, depending on the characteristics of the microalgae. However, the production of fish and animal feed by microalgae can significantly save the need for arable land, e.g. in comparison to growing soy-beans. As the illumination is more efficient and the productivity is higher in closed reactors, the space requirement is also lower compared to open pond systems.

Several small-scale trials with algae CO_2 capture have been carried out in the cement industry, e.g. in cement plants in Sweden, Turkey, France, Canada, Brazil, Portugal, etc. The tests with real flue gas from the cement kilns showed that the algae were not affected by the impurities of the flue gas. Furthermore, a sufficient growth rate of the algae was found. Another microalgae project on a larger scale is being planned in a Taiwanese cement plant with a 20 hectare production. Through this, the CO_2 emissions of the cement plant could be reduced by 4,800 t/yr.

Impact on energy efficiency

thermal: increase; exact figures
not available [MJ/t cli]

electric: increase; exact figures
not available [kWh/t cli]

Remark: The required electricity for algae capture has to be sourced from renewable energies.

CO$_2$ reduction potential

direct: decrease up to 750 [kg CO$_2$/t cli]   indirect: not applicable [kg CO$_2$/t cli]

Material input

water, nutrients   exact figures not available [t/t cli]

The main influencing parameters are

- Composition of the flue gas, trace components (e.g. SO$_x$, NO$_x$)
- Temperature, pH value, type of nutrients
- Algal physiology

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t 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

Conditions, barriers, constraints

- Large land areas are required for algae cultivation
- Large quantities of nutrients are required
- Not feasible in the dark.

4   Annex I: Key assumptions

Technical and financial calculations are based on following key assumptions:

Cement plant:

One reference plant based on CSI/GNR data GNR-2014 world average:

Kiln type: Predominantly characterised as dry process

- 70% dry process with preheater and precalciner (PHPC)
- 14% dry process with preheater (PH) without precalciner
- 16% mixed kiln types (incl. 3% long dry, 2% semi-wet/semi-dry, 2% wet/shaft)

Prices/costs:

- Based on world averages and estimates (fuel, electricity, investment, operation)
- For certain technologies, especially the use of alternative fuels, alternative raw materials and other main constituents, central European technology experiences and conditions were taken as a basis
- No depreciation considered in operation cost
- No discount rate
- No inflation
- Prices 2014, 2013, 2010
- Future price development of fuels and electricity estimated by OECD/IEA (ETP 2016)
- No CO_2 cost effect of Emission Trading, Clean Development Mechanism, Joint Implementation, etc.

Learning rates:

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

5   Annex II: Performance data of reference plant and used cost figures

Definition of reference plant (GNR-2014 data used for CSI/ECRA Technology Papers 2017)

Parameter		Unit	Reference plant (state of the art plant)
kiln type		---	dry process
clinker annual capacity		t cli/year	2 Mio.
clinker capacity		t cli/day	6000
clinker production		t cli/year	1.63 Mio.
cement production		t cem/year	2.17 Mio.
clinker/cement factor		t cli/t cem, %	75.2
raw meal/clinker factor		t RM/t cli, ---	1.55
fuels: (validated to fuel energy requirement)			
- fossil fuel (coal)		% thermal energy	84
- alternative fuels		% thermal energy	10.2
- biomass fuels		% thermal energy	5.8
specific fuel energy demand		MJ/t cli	3510
specific electric energy demand		kWh/t cem	104
share of electric energy demand for clinker production		%	51
specific electric energy demand for clinker production		kWh/t cli	70
specific CO_2 emission of electricity production		t CO_2/MWh	0.5
electric energy cost		Eur/ MWh	83.9
specific electric energy cost for clinker production		Eur/t cli	5
gross CO_2 per t clinker		kg CO_2/t cli	842
process CO_2 per t clinker		kg CO_2/t cli	536
gross CO_2 per t cement(itious)		kg CO_2/t cem	633
fuel costs (coal)		€/t	69.6
specific fuel costs (coal)		€/GJ	2.68
alternative fuel cost	2016	€/t	10.44
	2030		27.3
	2050		71.3
investment costs	2 Mio. clinker annual capacity	€/t annual capacity	130
		Mio. €	260
investment costs	1 Mio. clinker annual capacity	€/t annual capacity	170
		Mio. €	170
investment costs	0.5 Mio. clinker annual capacity	€/t annual capacity	250
		Mio. €	125
operational costs (excl. depreciation)		€/t cli	19.5
exchange rate for US Dollar/Euro		US $/€	1,1

6   Annex III: References

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7 Annex IV: List of new developed and updated papers

CSI/ECRA Technology Papers 2017 list of new developed and updated papers

2. State of the art papers

No.	Title	Reference TP2009
1	Thermal efficiency of cement production: state of the art an long-term perspective	1
2	Electric efficiency of cement production: state of the art and long-term perspective	2
3	Alternative fuels, raw materials and biomass use in the cement industry: long-term perspective	3
4	Recuction of clinker content in cement: long term perspective	4
5	New binding materials: long-term perspective for application in the cement industry	new
6	Carbon Capture and Storage (CCS): long-term perspective for application in the cement industry	5
7	Carbon Capture and Use (CCU): long-term perspective for application in the cement industry	new

3. Technology papers

Reference to State of the art paper	Technological topic	No.	Title	Reference TP2009
Thermal efficiency	Clinker process technology	1	Improve raw mix burnability e.g. by mineralisers	1
Thermal efficiency	Clinker process technology	2	Change from long kilns to preheater/precalciner kilns	2
Thermal efficiency	Clinker process technology	3	Preheater modification (e.g. cyclones with lower pressure drop)	3
Thermal efficiency	Clinker process technology	4	Additional preheater cyclone stage(s)	6
Thermal efficiency	Clinker process technology	5	Increase of kiln capacity	12
Thermal efficiency	Clinker process technology	6	Retrofit mono-channel burner to modern multi-channel burner	13
Thermal efficiency	Clinker process technology	7	Oxygen enrichment technology	7
Thermal efficiency	Clinker process technology	8	Efficient clinker cooler technology	4
Thermal efficiency	Waste heat recovery (WHR)	9	Waste heat recovery, Steam	new, 5
Thermal efficiency	Waste heat recovery (WHR)	10	Waste heat recovery, ORC	new, 5
Thermal efficiency	Waste heat recovery (WHR)	11	Waste heat recovery, Kalina Cycle	new 5
Alternative fuels, raw materials, biomass	Alternative fuels, raw materials, biomass	12	Alternative de-carbonated raw materials for clinker production	9
Alternative fuels, raw materials, biomass	Alternative fuels, raw materials, biomass	13	Fuel switch (coal/petcoke →oil/gas/pure biomass)	11
Alternative fuels, raw materials, biomass	Alternative fuels, raw materials, biomass	14	Alternative fuels, including biomass, replacing conventional fossil fuels	10
Alternative fuels, raw materials, biomass	Alternative fuels, raw materials, biomass	15	Pre-treatment of alternative fuel (grinding, drying)	new
Alternative fuels, raw materials, biomass	Alternative fuels, raw materials, biomass	16	Gasification or pre-combustion of alternative fuels	new
Alternative fuels, raw materials, biomass	Alternative fuels, raw materials, biomass	17	Hydrothermal Carbonisation (HTC) and Torrefaction	new
Electric efficiency	Process management	18	Upgrade plant automation/control package	8
Electric efficiency	Process management	19	Variable speed drives	18
Electric efficiency	Process management	20	Auxiliary system efficiency	new, 18
Electric efficiency	Process management	21	Energy management	new, 18
Electric efficiency	Process management	22	Optimized cement plant operation with renewable power	new, 18

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3. Technology papers

Reference to State of the art paper	Technological topic	No.	Title	Reference TP2009
Electric efficiency	Cement process technology, grinding	23	Cement grinding with vertical roller mills and roller presses	15
Electric efficiency	Cement process technology, grinding	24	High efficiency separators	16
Electric efficiency	Cement process technology, grinding	25	Optimization of operating parameters of ball mills	17
Electric efficiency	Cement process technology, grinding	26	Separate grinding of raw material components	19
Electric efficiency	Cement process technology, grinding	27	Advanced grinding technology	20
Electric efficiency	Cement process technology, grinding	28	Separate grinding and blending by fineness	new, 20
Electric efficiency	Cement process technology, grinding	29	Increased cement performance by optimized particle size distribution (PSD)	new, 20
Electric efficiency	Cement process technology, grinding	30	Optimized use of grinding aids	new, 20
Reduction of clinker content	Cement products	31	Further reduction of clinker content in cement by use of granulated blast furnace slag	21
Reduction of clinker content	Cement products	32	High performance cements and concretes resulting in the reduction of CO_2	new, 22
Reduction of clinker content	Cement products	33	Impact of very high/very low lime saturation factor	23
Reduction of clinker content	Cement products	34	Further reduction of clinker content in cement by use of fly ash	24
Reduction of clinker content	Cement products	35	Further reduction of clinker content in cement by use of natural pozzolanas	25
Reduction of clinker content	Cement products	36	Further reduction of clinker content in cement by use of natural calcined pozzolanas	new, 25
Reduction of clinker content	Cement products	37	Further reduction of clinker content in cement by use of other materials	26
New binding materials	New binding materials	38	Alkali-activated binders	27
New binding materials	New binding materials	39	Cements based on carbonates or on carbonation of calcium silicates	new, 27
New binding materials	New binding materials	40	Other low carbonate clinkers: pre-hydrated calcium silicates	new, 28
New binding materials	New binding materials	41	Other low carbonate cements - Belite cements	new, 28
New binding materials	New binding materials	42	Other low carbonate clinkers: (belite) calcium sulfoaluminate clinker	new, 28
Carbon Capture and Storage (CCS)	Carbon Capture	43	Oxyfuel Technology	30
Carbon Capture and Storage (CCS)	Carbon Capture	44	Post-combustion capture using absorption technologies	31
Carbon Capture and Storage (CCS)	Carbon Capture	45	Post-combustion capture using membrane processes	32
Carbon Capture and Storage (CCS)	Carbon Capture	46	Post-combustion capture using solid sorbents: Ca looping	new, 33
Carbon Capture and Storage (CCS)	Carbon Capture	47	Post-combustion capture using solid sorbents: Mineral carbonation	new, 33
Carbon Capture and Use (CCU)	Carbon Use	48	CO_2 use: basic chemicals, urea, formic acid, polymers	new
Carbon Capture and Use (CCU)	Carbon Use	49	CO_2 use: power-to-gas (CH_4)	new
Carbon Capture and Use (CCU)	Carbon Use	50	CO_2 use: power-to-liquids (CH_3OH)	new
Carbon Capture and Use (CCU)	Carbon Use	51	CO_2 use: Enhanced Oil Recovery (EOR)	new
Carbon Capture and Use (CCU)	Carbon Use	52	CO_2 use: Algae capture and fuel production, biofuels	new

Annexes

Key assumptions for technical and financial calculations		Annex I	Key assumptions	Annex I
Reference plant data based on GNR-2014 world avgerage		Annex II	Performance data of reference plant and used cost figures	new, Annex II
References		Annex III	General References, Additional specific references for technology papers	new
CSI/ECRA Technology Papers 2017 list		Annex IV	List of new developed and updated papers	new

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