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Process technology for efficient and sustainable cement production

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ABSTRACT

Over the years technology in the cement industry has been further developed with a growing focus on sustainable, cost- and energy-efficient production. While significant steps may not seem visible on a year to year basis, the medium-term view shows notable progress. The trend of increasing the capacity of cement kilns has slowed down in recent years — maximum clinker output still lies between 12,000 and 13,000 tpd. Burning and cooling technologies have progressed, especially with respect to burners specifically designed for the co-incineration of high levels of alternative fuels. Taking into account all process-integrated measures, thermal process efficiency reaches values above 80% of the theoretical maximum. The grinding of raw materials and cement has been in the focus of better energy utilisation, but product quality is also of the highest importance. In terms of sustainable production, NO_x abatement and CO_2 capture and its reuse remain in the focus of extensive research.

1. Introduction

Over the years technology in the cement industry has developed with a growing focus on sustainable and also cost and energy efficient production. While significant steps may not seem visible on a year to year basis, the medium-term view shows notable progress. The drivers for progress are certainly cost-based, but at the same time the cement industry, together with its equipment suppliers, has always strived to improve the overall efficiency and sustainability of the cement production process. Substantial energy savings have been achieved in recent years, and product-related emissions of CO_2 and other parameters have also been significantly reduced.

The trend of increasing the capacity of cement kilns has slowed down in recent years — maximum clinker output now lies between 12,000 and 13,000 tpd. There are good technical and economic reasons for this. The slowdown of the economy in many regions of the world may also have contributed to this trend. While notable growth for the BRIC countries (Brazil, Russia, China, India) is expected up to 2020, this growth is expected to level out in the years 2020 to 2030. However, major growth until 2030 can be expected from the "SETIVIM-countries" (Saudi Arabia, Egypt, Turkey, Iran, Vietnam, Indonesia and Mexico), as well as the "Next 7" (Algeria, Morocco, Nigeria, Pakistan, Malaysia, Thailand and the Philippines) as main drivers [1].

No breakthrough technologies are currently in sight with respect to clinker burning. Fourth generation clinker coolers are available from several suppliers and can be seen as state of the art. Cooler efficiencies of about 75% of the theoretical maximum can usually be achieved. Some developments have been made in burner technology, especially with respect to burners specifically designed for the co-incineration of high levels of alternative fuels. Taking into account the process-integrated drying of raw materials, other main constituents and fuels, the efficiency of the thermal process reaches values above 80% of the theoretical maximum [2]. The grinding of raw materials and cement has been in the focus of better energy utilisation, but product quality is also of highest importance. Therefore, new research approaches have been initiated focusing on the questions of how to comminute more efficiently and how to fully control particle size distribution. NO_x abatement on the basis of high efficiency selective non-catalytic reduction (SNCR) as well as selective catalytic reduction (SCR) has been tested in pilot and demonstration plants; CO_2 capture is the subject of intensive research with a strong focus on the potential reuse of CO_2. With respect to further increase materials and fuel efficiency, the substitution of natural fuels and raw materials by alternative ones is under on-going positive development. Many other examples can be given. Nevertheless, challenges remain and the cement industry will certainly continue to develop its technology, always in cooperation with the various equipment suppliers.

2. Thermal process technology

Energy utilisation in the cement industry has always been optimised for economic reasons; therefore, the potential for further optimisation is comparatively low. In 2010, the "Cement Technology Roadmap" of the International Energy Agency (IEA) [3] showed that at a global level, energy efficiency can only contribute a maximum of a further 10% towards the reduction of the CO_2 emissions of the global cement industry. A VDZ case study on Germany [4] revealed a maximum savings potential of 14%, even if all kilns and cement mills in Germany were rebuilt as completely new on "greenfield sites", which is certainly

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an unrealistic scenario just for economic reasons. However, alternative fuels can contribute considerably to the energy requirement, saving fossil fuels and at the same time in many cases lowering the CO_2 emissions of the respective kiln.

The reason for the very limited additional potential savings of thermal energy is the necessary heat for the clinker production process. Fig. 1 shows the heat flows, the thermal input, the use for clinkering and drying, and the remaining waste heat flows that might be utilised. However, the remaining waste heat is already used to a high degree, indicated by the already low temperatures of these flows, which does not allow a further efficient recovery of energy at this temperature level. Taking into account all the thermal energy supplied to the process, all energy utilised as well as the energy that cannot be utilised due to the low temperature level, the overall thermal efficiency of the process exceeds 80% of the theoretical maximum, which is among the highest of all industrial processes [4].

Fig. 2 depicts the overall cement-related energy demand including electrical and thermal energy, as derived in the case study for Germany [4]. While the overall demand seems to have been nearly constant over recent years due to the above mentioned effects, the figure clearly shows that the use of alternative fuels can significantly contribute to reduce thermal energy from fossil sources.

Electrical energy only comprises between 10 and 15% of the overall energy demand for cement production but is a notable cost driver [4,5]. Over the last decades the average specific electrical energy consumption has decreased (Fig. 3) [6]. However, there are counteracting effects: CO_2-emissions can be significantly reduced by the increased use of blast furnace slag as a cement constituent but this is more difficult to grind and consequently requires more energy for grinding. Also customer requirements for higher product fineness in some markets, and finally growing requirements for exhaust gas cleaning, be it for dust abatement or NOx reduction, cause an additional electrical and also thermal energy demand and have contributed to an increase in the product specific electrical energy consumption [4].

2.1. Alternative fuels

In recent years, the worldwide use of alternative fuels has increased significantly in many markets because their use may reduce the demand for fossil fuels and can – depending on the type of alternative fuel – increase the overall cost efficiency of the respective plant. Moderate substitution rates may be reached by the use of widely available bulky materials (e.g. entire tyres) combusted in the kiln inlet. Further substitution requires high-quality or even tailor-made alternative fuels with guaranteed constant moisture contents, particle sizes and heating values to avoid possible issues regarding process conditions and clinker quality.

The fluctuation in the moisture content of a given alternative fuel derived from selected industrial wastes is shown as an example in Fig. 4. The cement industry has developed techniques and burning strategies to homogenise such varying properties through specialised on-site pre-treatment [7]. In the case of moisture content, dedicated drying strategies such as drum driers or mill driers can substantially lower the moisture [8] and can also improve the burning characteristics of the waste [9], utilising in many cases waste heat that cannot be used otherwise. Again, these measures go along with increased treatment costs and also in most cases with an increase in electrical energy consumption. Computational fluid dynamics (CFD) simulation may help to optimise the combustion including optimal injection points [2]. In any case, the simulation requires a comprehensive specification of the fuels used in order to representatively illustrate the particle trajectory and combustion (Fig. 5).

To increase energy efficiency by ensuring a complete combustion of alternative fuels, fuels can be gasified in fluidised or fixed bed chambers or suspension flow processes. Different concepts for combustion chambers for calciner systems have been developed and installed in the past years [10–12]. Enabling longer retention times and the handling of coarse materials with more heterogeneous properties, they add a new level of flexibility regarding the choice of fuel.

Separate combustion chambers using a burner design similar to rotary kiln burners provide longer retention times than conventional calciner combustion systems without the need of further combustion points [10]. Also pyrolysis systems can provide a sufficiently long retention time and cope with coarse materials by drying and pyrolising alternative fuels in a rotational system before fully combusting in the calciner and kiln inlet [11]. A different approach is the use of a blower system in a step combustor to transport burnt out fuel fractions within the gas stream into the calciner while heavy fractions remain within the chamber until fully combusted [12]. In all three systems, hot tertiary air and preheated raw meal are used to adjust optimal conditions in the combustion chamber.

Moreover, a moderate oxygen enrichment in the combustion air can support the complete fuel particle burnout, which allows an increased substitution rate or the utilisation of slow-burning alternative fuels [13].

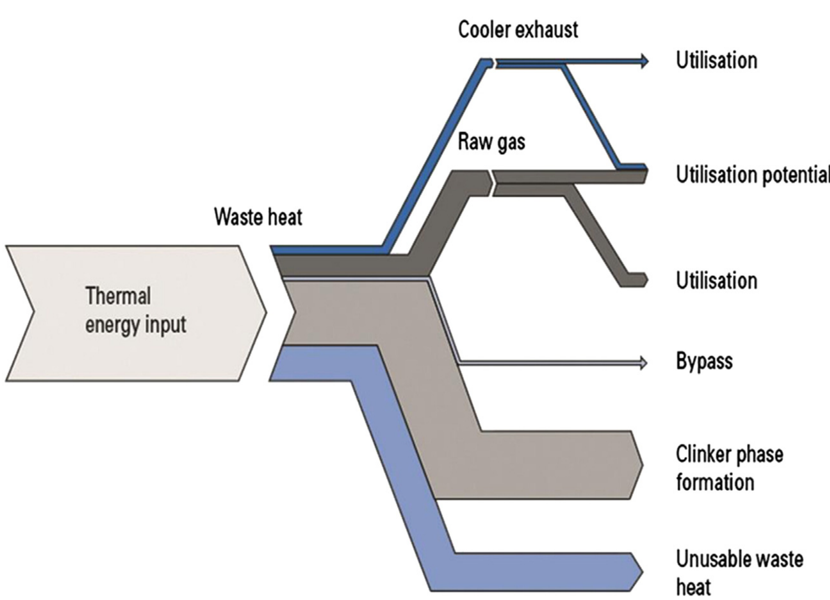

Fig. 1. Thermal energy and waste heat flows for the clinker production process. The relative sizes of the energy flows correspond to the respective thermal energies in the process.

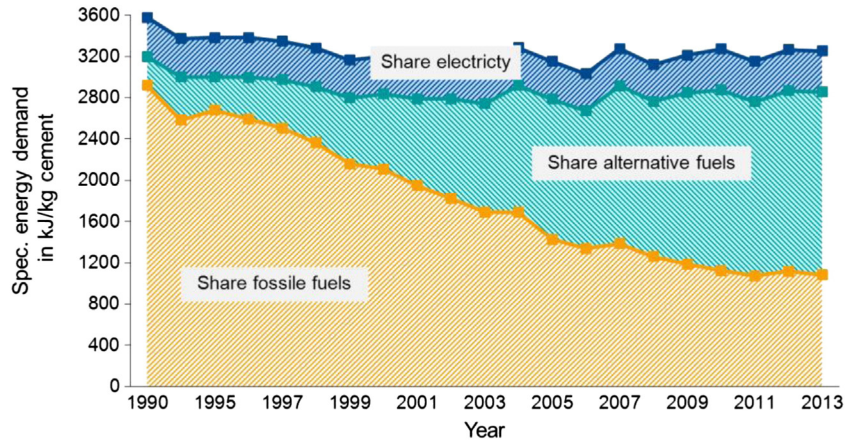

Fig. 2. Development of specific energy demand in the German cement industry [2].

Due to the high costs for oxygen production this measure is not widespread.

Alternative fuels may exhibit differing chemical compositions compared to fossil fuels, for which reason the raw mix has to be adapted to produce comparable clinker compositions on site, but the kiln's operation is also influenced. Depending on the overall raw material composition and the composition of the alternative fuels, a gas bypass may be required which allows to extract a certain amount of gas at the kiln inlet in order to reduce inner cycles (Fig. 6). Many bypass systems have been installed in cement plants worldwide during the past two decades, and the main technical questions such as removal efficiency, gas and dust treatment have therefore been solved satisfactorily [14].

2.2. Waste heat recovery

Regarding the sustainability of the cement production process, waste heat recovery (WHR) provides a potential to recover the energy from the clinker burning process. The technology was spearheaded by Japanese companies before being introduced to the Chinese market in 1998. China since then has become market leader in terms of installed WHR systems, driven by incentives as well as national energy efficiency regulations [15]. The number of installations generating electrical power from the waste heat of cement plants has risen strongly in the past years. While in 2009 525 installations were reported, the number had increased to 865 by 2012. The worldwide distribution in the cement industry is focussed mainly on the Asian market where more than 95% of all WHR installations are operated, with a corresponding 85% in China [1,16]. Driven by rising prices for power and fuel, concerns about grid reliability and commitment to sustainable development, the interest in WHR has expanded among global companies [15].

The choice of the technology applied in a specific case depends strongly on the available heat flow rate but mostly of all on the available temperature level. The most common conventional water steam cycle can operate at heat source temperatures of as low as 300 °C. For lower temperatures, the Organic Rankine Cycle (ORC), utilising organic compounds as process fluids, or the Kalina Cycle, utilising a water-ammonia solution are available [17]. Proven in other industries, the latter are on the rise in the cement industry since the number of references has increased which may be due to the fact that improvements in clinker production have led to lower exhaust gas temperatures [16]. Nevertheless, conventional steam technology still accounts for 99% of the installed WHR systems with only a total of nine ORC and two Kalina Cycle systems installed so far [15]. The decision on whether the installation of a waste heat recovery system is reasonable, depends strongly on the specific situation of the plant site and the economics.

3. Sustainable production — emissions

State-of-the-art process-integrated measures as well as dedicated secondary abatement technologies ensure low emissions while keeping the influence on the kiln operation at a minimum. Recently, special focus has been placed on mercury, NO_x and CO_2 emissions.

3.1. Mercury

The Minamata Convention on Mercury as a global and legally binding treaty is targeted at the worldwide reduction of mercury

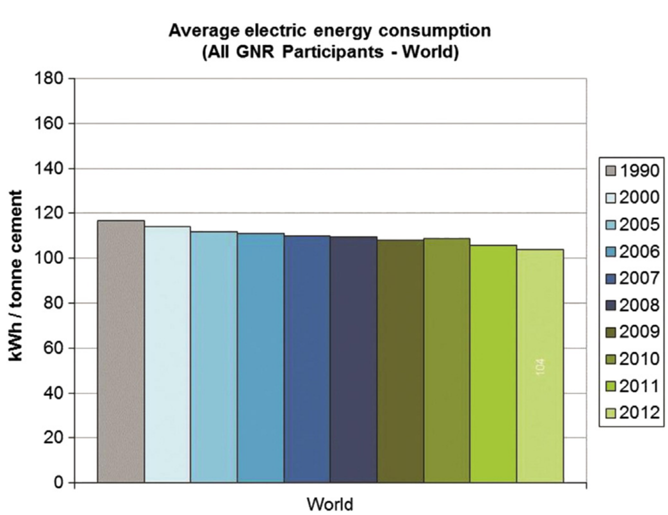

Fig. 3. Average electric energy consumption (all study participants — world) [6].

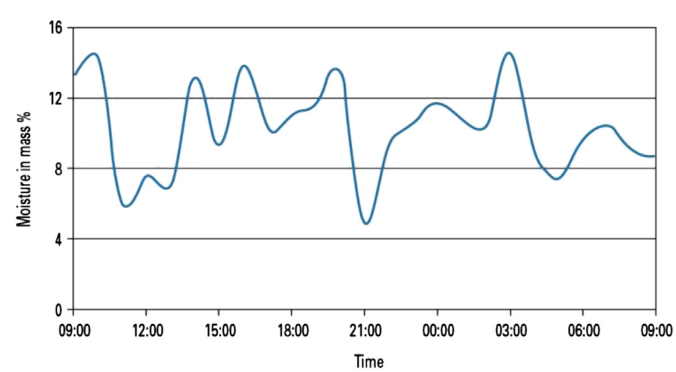

Fig. 4. Moisture fluctuation of alternative fuels (fluffy materials, RDF) [2].

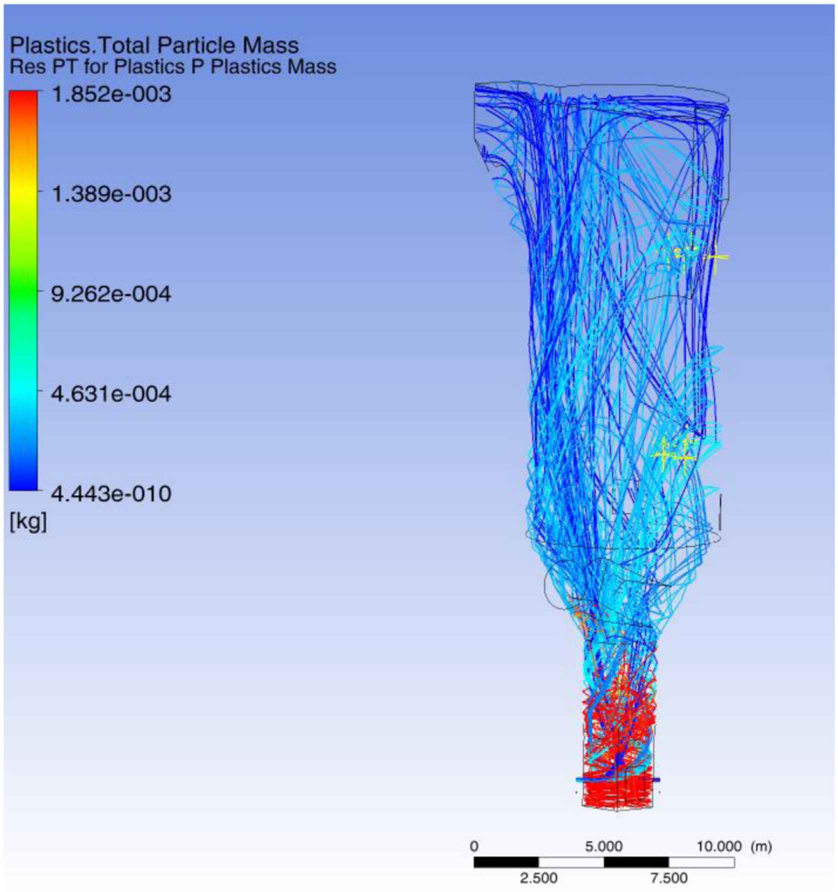

Fig. 5. Particle tracks of plastic materials from SRF, particle mass shown by colour [2]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

emissions, regulating their anthropogenic causes. It was initiated by the United Nations Environmental Programme (UNEP) Governing Council in 2009 and opened for signature in October 2013, and will come into force after being ratified by 50 countries. UNEP addresses the anthropogenic mercury sources in its global mercury assessment including a breakdown of the relative contributions of the estimated mercury emissions to air from anthropogenic sources in 2010 in Fig. 7 [18].

The cement industry's share in these emissions may have been overestimated since it does not correspond to the industry's experiences and it has therefore been challenged by the European CEMBUREAU and the CSI (Cement Sustainability Initiative).

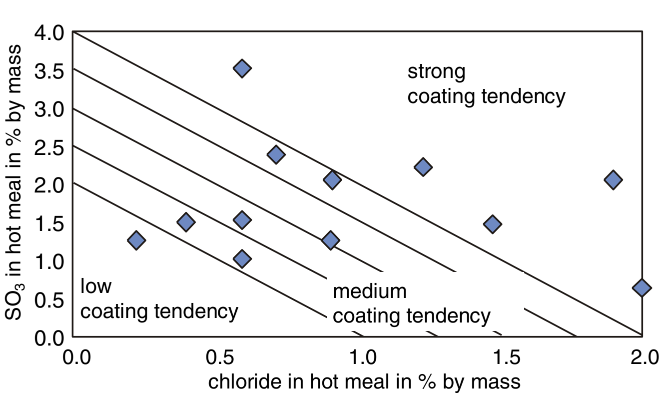

Fig. 6. Dependency of coating tendency and sulfur/chlorine content in hot meal of the lowest cyclone stage.

The behaviour of mercury in the clinker burning process is well understood. Like other trace elements, mercury is introduced into the production process through all raw materials and fuels. The respective concentrations are low and depend on the type and origin of the various fuels and raw materials, e.g. within a quarry trace element concentrations reflect the variation of the specific geological distribution. Owing to their high volatility, mercury and its compounds are adsorbed on cement kiln dust at comparatively low temperatures with respect to other trace elements in the burning process [19].

In cases where higher mercury emissions may occur, abatement strategies are required.

Monitoring the mercury input from alternative materials and fuels as well as dust shuttling to avoid the build-up of mercury cycles in the kiln/preheater system are proven measures for mercury control. Long-term balance tests have shown that shuttling precipitated dust in combination with a sophisticated temperature control provides a high removal efficiency when conducted in the mill-off mode [20]. As a last resort, additional techniques known from power plants such as the injection of activated carbon or other sorbents may further enhance the removal efficiency [21].

Continuous measurement of mercury emissions remains a challenge due to the fact that mercury can occur as elemental mercury (Hg(0)) and oxidised mercury (Hg(I) and Hg(II)). Mercury compounds contained in the gas stream need to be completely reduced for a reliable measurement. For this procedure different technologies are available. These are a wet chemical procedure, thermocatalytic reduction or thermal reduction under temperatures of about 1000 °C. In practical application, long-term stable operation of the measuring instruments

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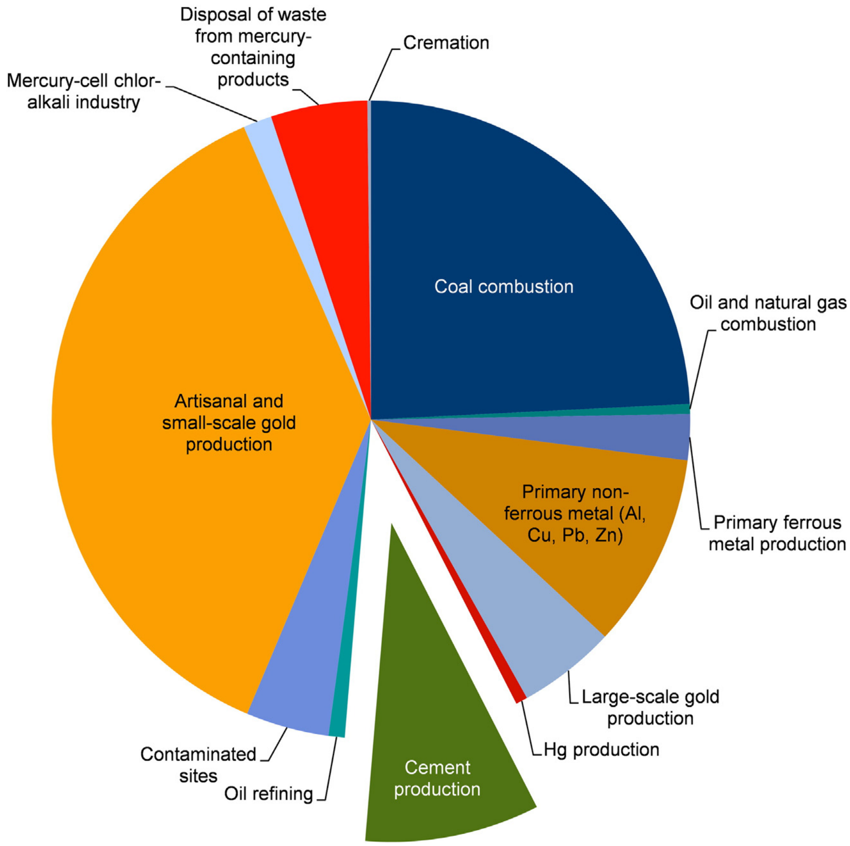

Fig. 7. Relative contributions to estimated mercury emissions to air from anthropogenic sources in 2010 [18].

has been challenging, but reliability and maintenance requirements were able to be optimised [20].

3.2. NO_x

In recent years the cement industry's NO_x emissions have been significantly reduced by optimising existing and proven technologies as well as introducing technologies new to the cement industry. Being widely applied for NO_x abatement, the SNCR (selective non-catalytic reduction) process is based on the injection of ammonia water or urea solution to reduce nitrogen oxides in a temperature range of 850–950 °C. However the process may lead to an increase in NH_3 emissions. Efforts were therefore made to improve the technology (high efficiency SNCR), increasing abatement efficiency and also lowering NH_3 emissions. It should be pointed out that bypass gases are more difficult to subject to SNCR, thus limiting the ultimate abatement capability [22].

The SCR (selective catalytic reduction) technology is based on the same principle as the SNCR technology but uses a catalyst to bring the required reaction temperature into a range of 250–400 °C. Its potential in the cement industry has been investigated in trials and pilots in the European cement industry [23–25], focussing in recent full scale demonstration projects on the possible configurations of an SCR installation in the exhaust gas duct (high dust [26], low dust [27] and semi-dust [28]). The experiences made regarding the individual characteristics of each of the aforementioned NO_x abatement strategies are summarised in Table 1.

3.3. CO_2 reduction in the cement industry

The cement industry has reduced its greenhouse gas emissions per tonne of cement over the last two decades through a combination of different means in order to address the environmental imperative of climate change. The reduction methods are in line with those indicated in several roadmaps, which underline the requirement of cutting industrial CO_2 emissions by half from the 2009 level by 2050 [3]. Due to the local conditions on which these roadmaps are based the predicted routes to achieve the overall reduction target differ (Fig. 8) [3,4,30–32]. The technologies for the cement industry which are available today, however, such as increasing energy efficiency, the reduction of clinker content in the cement and the application of alternative fuels, can only partly contribute to this objective.

The biggest lever to reduce anthropogenic CO_2 emissions is the utilisation of alternative fuels due to their lower carbon content as well as their biogenic fraction (Fig. 9). Therefore, the importance of alternative fuels continues to grow globally due to the positive economic and environmental aspects. However, due to different and varying properties — such as in most cases higher moisture content-,

Table 1
Assessment of NO_x abatement by SNCR and SCR [29].

Technology	Assessment
High efficiency SNCR	– Costs lower than SCR – Abatement efficiency limited – Risk of higher NH_3 emissions
High dust SCR	– Optimum temperature after preheater, no preheating required – Less complexity than low dust scheme – Dust load high, potential impact on clogging and catalyst's activity
Low dust SCR (tail end)	– Dust load very low, little risk of clogging higher, less risk to loose catalyst's activity – Gas to be reheated – As compared to high dust SCR: less catalyst volume required
Semi dust SCR (For special process provisions)	– Good cost/benefit ratio – Requires high temperature ESP – As compared to high dust SCR less clogging potential – Less experience as compared to other schemes

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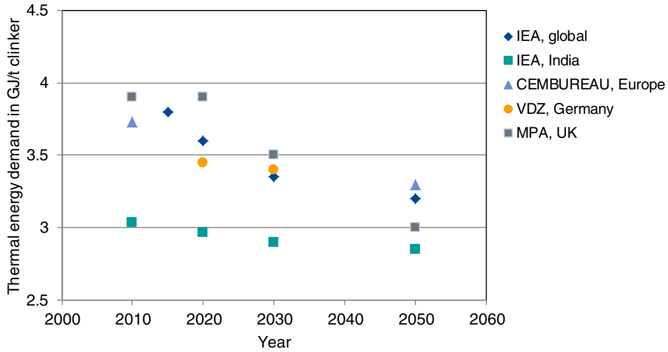

Fig. 8. Roadmap prediction of the thermal energy development until 2050 [3,4,30–32].

the process-integrated drying can result in higher thermal energy demand for the kiln. In general, when alternative fuels are applied, it is necessary to adapt the process to the differing fuel properties [33].

A lower clinker-to-cement-ratio also results in less energy demand per unit of cement because the energy and CO_2 emissions from the decarbonation of the limestone are saved. The most important clinker replacing constituents are fly ash, slag, limestone and pozzolana. Furthermore, good results on the use of calcined clays as a main constituent in cement are being reported [34,35]. It has to be taken into account that the blended cements that contain these clinker replacement materials may have different or even limited properties compared to Ordinary Portland Cement. This is subject to many investigations, in particular with a strong focus on the durability of concrete produced by using these cements. In general, some of these main constituents other than clinker may have a limited availability, sometimes only on a regional basis, which of course limits their application in cement.

However, the International Energy Agency expects that these conventional measures will only partly fulfil the reduction target for CO_2 emissions which has been set for 2050 [3]. This is the reason why carbon capture technologies are being discussed in order to "close this gap". In this context the capture of carbon dioxide and its geological storage, often referred to as "carbon capture and storage" (CCS), or its capture and reuse (CCR) in valuable products, is currently being investigated for the cement industry in order to elaborate options, constraints and related costs. For the purpose of CO_2 capture different categories of technologies are being discussed, but only two seem feasible in the cement clinker production: post-combustion capture as an end-of-pipe solution and the oxyfuel process as an integrated technology. Research activities currently on-going in the field of post-combustion capture include chemical absorption, adsorption, membrane, mineralisation and calcium looping technologies. Those technologies are currently being investigated in pilot plants (e.g. Brevik [36], Skyonic projects [37],

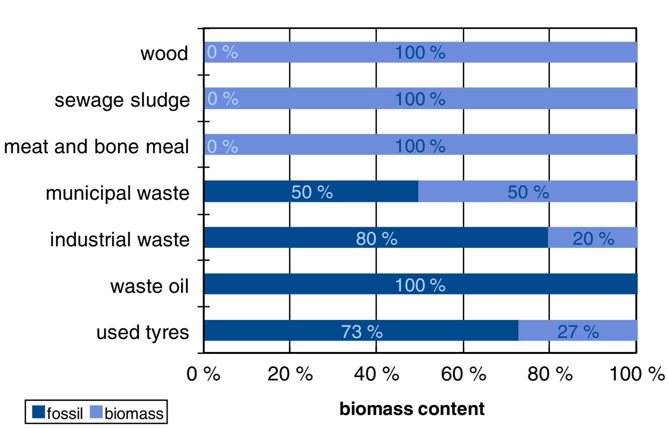

Fig. 9. Biomass content of different types of alternative fuels.

Taiwan Cement [38]). Due to the already high level of knowledge, the post-combustion technology is being discussed as a potential capture method for short term implementation in 2020.

Oxyfuel technology is still at a basic research status, because the integration of the technology requires substantial adaptation of the process. It requires in particular the use of oxygen for combustion and the recirculation of flue gas – mainly CO_2 – as secondary air. The recirculation rate has a tremendous impact on the thermal energy demand and must be adapted to the specific situation at the kiln in question (see Fig. 10). It was shown that such a kiln can principally be designed and that under a CO_2/O_2 atmosphere clinker with the same quality can be produced as today in existing kilns [39]. Although different research projects have been conducted, detailed R&D is still needed before this technology can advance to pilot-scale, which would be the next technological step. As a pre-stage, ECRA is currently preparing a concept study for an oxyfuel pilot cement kiln [41]. Moreover, one cement producer is planning a pilot-scale test at its plant in France [42]. Due to the challenges involved with integration and the influences on the process and the material, a commercial application is not expected before 2030.

However, to what degree carbon capture could become a technically and economically feasible technology in the cement industry remains an open question. Besides legal or technological reasons it is first of all the overall cost which is extremely high and would not allow the respective plant to operate competitively (Fig. 11). For this reason there is always a significant risk that clinker and/or cement would then be imported from regions with lower CO_2 abatement costs, well described by the term "carbon leakage".

Against the background of the missing legal overall framework for CO_2 storage and the lack of storage capacities, the reuse of CO_2 might provide a better prospect for CO_2 capture in the cement industry. Power to gas projects [43,44], for example, have been initiated and might provide a good link between energy storage and CO_2 utilisation. To what extent such combined technology synergies will be technically and economically feasible for cement manufacture remains open at this time. The review of these groundbreaking indicative studies outlines the potential of such an approach but also underlines the need for further research in this field.

4. Efficient grinding

Comminution and especially cement grinding still account for the majority of the electrical energy demand of cement production. As Fig. 12 shows, between 60% and depending on cement properties up to 70% of the roughly 100–110 kWh of electrical energy per ton of cement are used for comminution processes [5,45]. It has to be noted that these values strongly depend on production fineness and therefore vary according to local market demands. The efficiency of large scale industrial comminution processes in general has to be regarded as low. However, it is not only energy efficiency, but also requirements for good reliability and versatility of the grinding processes that used to and still drives developments in grinding equipment [46].

While vertical roller mills (VRMs) are predominantly used for raw material grinding, different types of grinding systems are used for the finish grinding of cement. VRMs are well established, however, roller presses in conjunction with ball mills are also widely used. In any case, finish grinding operations containing ball mills are still frequently found on a global level. In terms of new installations globally, excluding China, the VRM is way ahead with 113 mills ordered in 2012 followed by the ball mill with 51 and high pressure grinding rolls (HPGR) with 27 new orders [1]. This is reflected in the latest technological trends: Most new equipment concepts are focusing on VRMs and their drive units [48–50]. In China, however, the situation is different. With 460 new mill orders in 2012, China's local market is not only much bigger than the rest of the world's, but in addition, a share of over 60% of the cement is produced on grinding systems with HPGRs [51,1].

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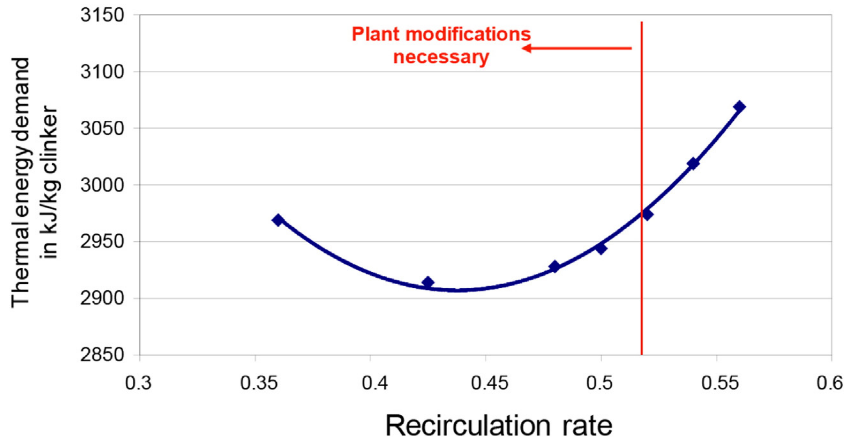

Fig. 10. Fuel energy demand of a full oxyfuel cement plant related to the recirculation rate [40].

Huge challenges to cope with increasing energy costs have also initiated the substitution of existing grinding equipment by new mills. However, in most cases such substitution goes along with an increase in production or an installation of new capacities [46]. Any finish grinding constellation has to be seen against the background of existing quality requirements as well as clinker reactivity and the availability of other main cement constituents. This also affects the final product in which the particle size distribution is nowadays controlled to a higher degree than in the past. Ball mills are known as reliable and easy to operate for cement grinding. However, their energy efficiency is still a challenge for the cement producers. This has an effect on different grinding constellations as well as on-going optimisation efforts. Today ball mills are still widely used. This is not only true for existing plants, but also for new grinding units recently built and still to be built. Consequently, nowadays strong focus is being placed on the better understanding of the grinding mechanisms in balls mills in order to optimise the mills correspondingly. Investigations have for example revealed a huge savings potential by the optimisation of ball charges [52,53].

Theory indicates that industrial comminution in general is more than one order of magnitude worse in energy efficiency than laboratory single particle comminution [54]. But single particle stressing is difficult to realise when dealing with industrial scale throughputs. The energy utilisation depends strongly on the type of stress, the stress intensity, the stress energy and also the transfer of the energy from the drive to the particles (energy transfer factor) [55]. Since these parameters and transfer factors are difficult to combine, the definition of "efficiency" in this context is quite complicated. In addition, current research is still investigating the micro-processes of comminution like for example the elastic and plastic deformation of particle beds [56] in order to fully understand grinding processes.

Besides sufficient theoretical models, data on the individual material properties is required in order to actually optimise cement grinding equipment. Cement clinker itself can already exhibit huge differences in grindability as Fig. 13 shows but also in granulometry depending on the chemical composition, burning and cooling conditions. Along with the increasing production of clinker-efficient products an on-going diversification of the product portfolio can be observed. To describe the comminution behaviour of these very different material compositions during intergrinding is very complex and the determination of optimum process parameters for a set of different products ground on one mill is difficult, especially as materials with different grindabilities like clinker, slag and limestone as shown in Fig. 13 are enriched in different size fractions during comminution. Fig. 14 shows as an example the enrichment of slag in the coarse fractions when interground with clinker [57].

These effects can be avoided by the separate grinding and blending of cements. Single components can be ground on suitable mill systems at higher efficiencies while particle size distributions can be better controlled compared to intergrinding. In addition, blending allows not only for more flexible production but also for additional degrees of freedom with regard to the overall particle size distribution. Taking into account the hardening and strength development of different materials as well as their grindabilities it is possible to design production- and resource-efficient cements [58]. But still not all effects of particle size distribution and the chemical composition on the final

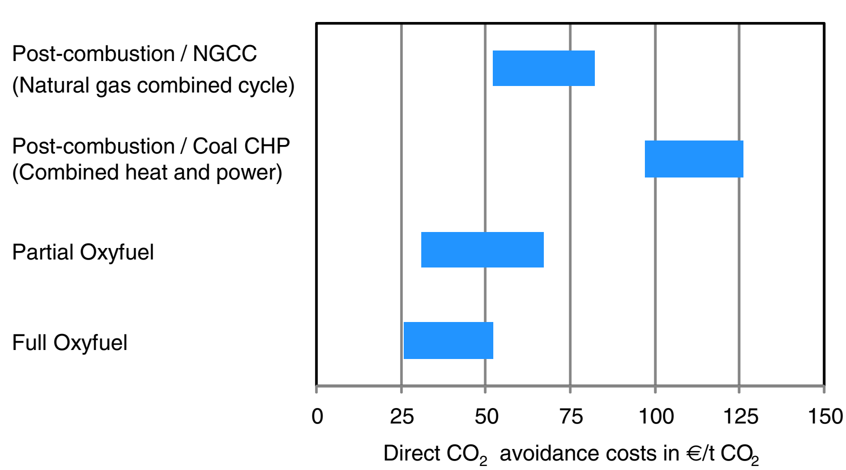

Fig. 11. Comparison of direct CO_2 avoidance cost (excl. transport and storage and indirect CO_2 emissions) for different capture technologies for a reference cement plant [33].

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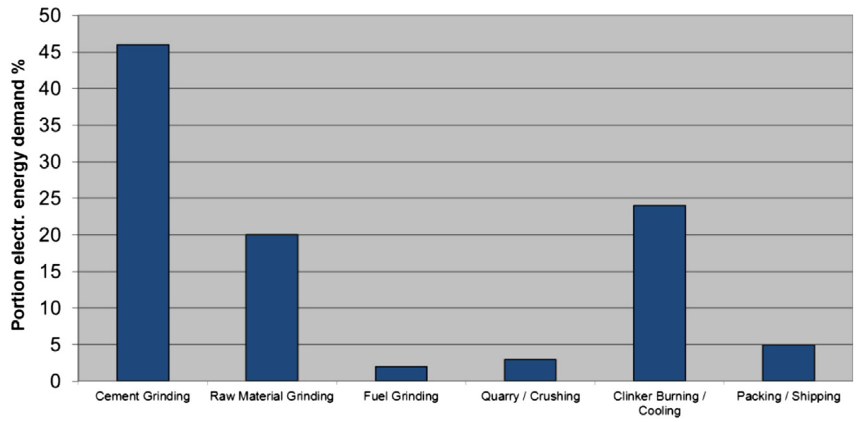

Fig. 12. Energy demand of plant units (based on data from the German cement industry) [47].

concrete properties – especially durability – have been fully understood. Process technology for separate grinding on the other hand is well known in general. In most cases existing mill systems can be enhanced by transport and storage facilities. But depending on the given plant layout and the product portfolio the individual technical solutions for separate grinding and blending can significantly differ. In order to further increase the efficiency of production raw materials, process technology and product design should all be considered together.

5. New cements — low-carbon cements

Today many different approaches are being examined with regard to new cement types which exhibit a lower energy demand and/or lower CO_2 emissions for their production than Ordinary Portland Cement (OPC). Ternary cements which are shortly to be standardised in Europe are one example [59]. Other approaches take advantage of existing experience, as is the case with belite-rich-cements. Furthermore, sulphoaluminate clinker or belite-calciumsulfoaluminate-ternesite systems are providing opportunities for new cement types in the future. A new concept is also being pursued in the case of CELITEMENT, which is based on calcium and silica as starting materials but which requires a hydrothermal process followed by a dedicated reactive grinding step.

Process-wise the technology for these new cement types is in principle available; various kiln systems including their coolers exist. They differ from conventional clinker production due to the fact that the stabilisation of the major mineralogical phase requires e.g. very specific temperature profiles in the kiln or cooling conditions [60]. The developments of these new cement types are discussed in detail in other papers in this volume.

Belite types of clinker have been well known for many years. These can be burned like OPC clinker but at lower temperatures of around 1250–1300 °C. A comparison of the cement properties of high belite cements and OPC highlights the optimised performance of a mix of both cements [61].

The main phase of sulphoaluminate clinker is ye'elimite (C_4A_3s). The clinker requires a burning temperature of about 1250 °C and is easy to grind. Corresponding cements show a setting time similar to OPC but exhibit different compressive strength developments [62].

The belite-calciumsulfoaluminate-ternesite (BCT) technology combines the different performance and durability characteristics of calcium-sulfoaluminate (CSA) cements and belite cements. CO_2 emissions of BCT clinker are around 30% lower than those from conventional OPC. BCT has been produced on a semi-industrial scale illustrating the good performance and high potential of this technology. As the next steps, the up-scaling and optimisation of the manufacturing technology to industrial dimensions are planned [63].

CELITEMENT is produced in an autoclave process with subsequent reaction grinding. The first field of application is assumed to be in special construction materials such as tile adhesives, fillers, plasters or mortars. Although the production technology is not based on conventional rotary kilns, the use of autoclaves for the mass production of building materials such as lime silica bricks is well established. The CELITEMENT process is in its pilot research status, comprehensive data about the material and the process, e.g. energy demand, are not yet available [64].

Due to their lower CO_2 emissions all these cements are sometimes called low carbon cements. Even if this declaration might not be perfectly correct it clearly underlines the endeavour of the producers to lower the carbon footprint of their product portfolios. To what degree these cements will find their way onto the market will depend on many factors. While a broad application of cements with well-tried and proven constituents such as the ternary cements (CEM II/C-M and CEM VI according to the European standard EN-197-1) seems to be possible in the near future, other new cements need to be developed from a research state to a full range of applications.

6. Outlook

The technology of cement production will without doubt be developed further in future years, as it has in the past. The challenges which

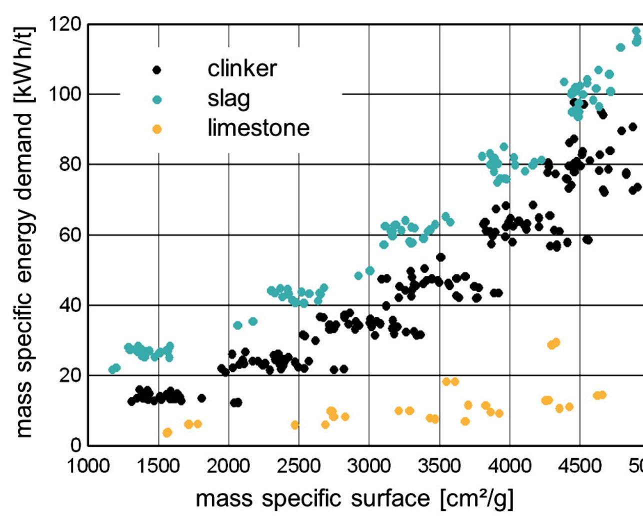

Fig. 13. Grindability of different clinker, slag and limestone samples determined by the test acc. Zeisel [57].

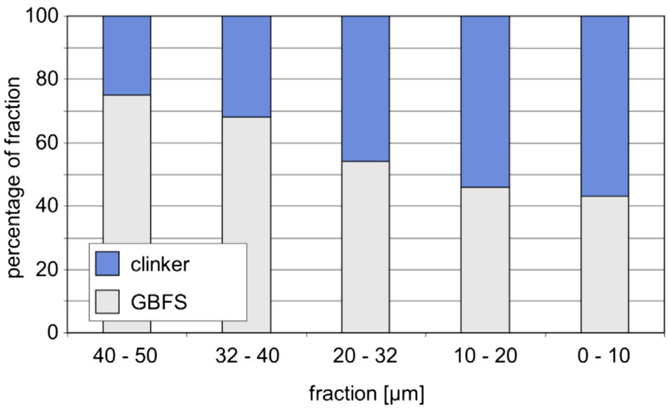

Fig. 14. Enrichment of ground blast furnace slag (GBFS) in coarse size fraction of a blast furnace slag cement (CEM III/A) which is interground with clinker [57].

remain for the cement industry are: to reduce production costs, and to keep a strong focus on quality, performance and cement's impact on concrete durability. Overall, CO_2 abatement in the context of regional and global climate negotiations remains a framework in which the cement industry will define its own carbon roadmap, taking into account the CO_2 emissions from the production process but also the tremendous benefit which cement provides for all societies, today and in the future.

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