

European Cement Research Academy

European Cement Research
Academy GmbH

Toulouser Allee 71
40476 Duesseldorf, GERMANY

Phone: +49-211-23 98 38-0

Fax: +49-211-23 98 38-500

info@ecra-online.org

www.ecra-online.org

Chairman of the Technical
Advisory Board: Ernest Jelito

Managing Director: Martin Schneider

Registration office: Duesseldorf

Court of registration: Duesseldorf

Commercial registration no.: 47580

THE ECRA TECHNOLOGY PAPERS 2022

State of the Art Cement Manufacturing

Current technologies and their future development

State of the Art Cement Manufacturing

Current technologies and their future development

This study was commissioned by the Mission Possible Partnership (MPP) and the Global Cement and Concrete Association (GCCA). 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, and in the medium and long-term future. It includes emerging technologies which aim to achieve net-zero CO₂ emissions in the production of clinker and cement. While the results have been developed and reviewed by ECRA in exchange with industry experts and with MPP and GCCA project partners, the opinions and views expressed are those of ECRA.

This update of the Technology Papers is a collaboration with the Mission Possible Partnership (MPP), an industry-backed alliance of more than 400 leaders from finance, industry, and policy. The leading voice on industrial decarbonisation, MPP is focused on action in this decade to accelerate decarbonisation and make net zero possible by mid-century. Founded by the Energy Transitions Commission, Rocky Mountain Institute, We Mean Business Coalition, and the World Economic Forum, MPP has mapped detailed transition strategies and real-economy milestones for seven hard-to-abate sectors which produce about 30% of global carbon emissions: aluminium, aviation, cement and concrete, chemicals, shipping, steel, trucking. Without immediate action, in a business-as-usual scenario these industries alone will exceed the world's remaining 1.5°C-aligned carbon budget by 2030.

www.missionpossiblepartnership.org

Please cite this report as follows:

European Cement Research Academy, Ed. *The ECRA Technology Papers 2022 - State of the Art Cement Manufacturing - Current Technologies and their Future Development*. Duesseldorf, 2022. Available at: <https://ecra-online.org/research/technology-papers>

Index of Contents

1	Introduction	6
2	Key assumptions	8
3	State of the art	9
3.1	State-of-the-art Paper No. 1: Thermal efficiency of cement production: State of the art and long-term perspective	9
3.2	State-of-the-art Paper No. 2: Electric efficiency of cement production: State- of-the-art and long-term perspective	11
3.3	State-of-the-art Paper No. 3: Alternative fuels, raw materials and biomass used in the cement industry: Long-term perspective	14
3.4	State-of-the-art Paper No. 4: Reduction of clinker content in cement: Long term perspective	17
3.5	State-of-the-art Paper No. 5: New binding materials: Long-term perspective for application in the cement industry	21
3.6	State-of-the-art Paper No. 6: Carbon Capture and Storage (CCS): Long-term perspective for application in the cement industry	24
3.7	State-of-the-art Paper No. 7: Carbon Capture and Use (CCU): Long-term perspective for application in the cement	27
3.8	State of the art Paper No. 8: (Re)carbonation: Long term perspective for the cement and concrete value chain	30
4	Technology papers	32
4.1	Technology Paper No. 1: Improving raw mix burnability e.g. through mineralisers	32
4.2	Technology Paper No. 2: Change from long kilns to preheater/precalciner kilns	34
4.3	Technology Paper No. 3: Preheater modification through cyclones with lower pressure drop	36
4.4	Technology Paper No. 4: Additional preheater cyclone stage(s)	38
4.5	Technology Paper No. 5: Increase of kiln capacity	40
4.6	Technology Paper No. 6: Retrofit mono-channel burner to modern multi-channel burner	42
4.7	Technology Paper No. 7: Oxygen enrichment technology	44
4.8	Technology Paper No. 8: Efficient clinker cooler technology	46
4.9	Technology Paper No. 9: Waste heat recovery: Steam	49
4.10	Technology Paper No. 10: Waste heat recovery: ORC	52
4.11	Technology Paper No. 11: Waste heat recovery: Kalina Cycle	54
4.12	Technology Paper No. 12: Alternative decarbonated raw materials for clinker production	57
4.13	Technology Paper No. 13: Fuel switch (coal/petcoke to oil/gas)	60
4.14	Technology Paper No. 14: Alternative fuels replacing conventional fossil fuels	62
4.15	Technology Paper No. 15: Pre-treatment of alternative fuel (grinding, drying)	65
4.16	Technology Paper No. 16: Pre-combustion chambers and gasification	68
4.17	Technology Paper No. 17: Hydrothermal Carbonisation (HTC) and Torrefaction	71
4.18	Technology Paper No. 18: Use of hydrogen as fuel	74
4.19	Technology Paper No. 19: Electrification, plasma and other technologies	77
4.20	Technology Paper No. 20: Recycled concrete fines as raw material for clinker production	80

4.21	Technology Paper No. 21: Advanced plant control and AI-supported control systems	83
4.22	Technology Paper No. 22: Variable speed drives for fans	85
4.23	Technology Paper No. 23: Auxiliary system efficiency	87
4.24	Technology Paper No. 24: Energy management	89
4.25	Technology Paper No. 25: Optimised cement plant operation with renewable power	91
4.26	Technology Paper No. 26: Cement grinding with vertical roller mills and roller presses	94
4.27	Technology Paper No. 27: High efficiency Separators	96
4.28	Technology Paper No. 28: Optimisation of operating ball mills	98
4.29	Technology Paper No. 29: Separate grinding of raw material components	100
4.30	Technology Paper No. 30: Advanced grinding	102
4.31	Technology Paper No. 31: Separate ultra-fine grinding and blending of cements	104
4.32	Technology Paper No. 32: Increased cement performance by optimised particle size distribution (PSD)	106
4.33	Technology Paper No. 33: Optimised use of grinding aids	108
4.34	Technology Paper No. 34: Reduction of clinker content in cement by use of granulated blast furnace slag	110
4.35	Technology Paper No. 35: Reduction of clinker content in cement by use of natural pozzolanas	113
4.36	Technology Paper No. 36: Reduction of clinker content in cement by use of natural calcined pozzolana	116
4.37	Technology Paper No. 37: Reduction of clinker content in cement by use of limestone or other materials	120
4.38	Technology Paper No. 38: Cements with very high limestone content	123
4.39	Technology Paper No. 39: Impact of very high/very low lime saturation factor	125
4.40	Technology Paper No. 40: Recycled concrete fines as a cement constituent	127
4.41	Technology Paper No. 41: Reduction of clinker content in cement by use of fly ash	131
4.42	Technology Paper No. 42: Reduction of CO ₂ by efficient use of concrete	134
4.43	Technology Paper No. 43: Alkali-activated binders	136
4.44	Technology Paper No. 44: Cements based on carbonates or on carbonation of calciumsilicates	138
4.45	Technology Paper No. 45: Other low carbonate clinkers: Pre-hydrated calcium silicates	140
4.46	Technology Paper No. 46: Other low carbonate cements - Belite cements	142
4.47	Technology Paper No. 47: Other low carbonate clinkers: (Belite) calcium sulfoaluminate clinker	145
4.48	Technology Paper No. 48: Carbon capture technologies	147
4.48.1	Introduction	147
4.48.2	Methodology and assumptions	147
4.48.3	Technology description	149
4.48.4	Impact on energy consumption and consumables	156
4.48.5	CO ₂ emission reduction potential	158
4.48.6	Technical Readiness	162

4.48.7	Investment figures and operational costs	163
4.48.8	Conditions, barriers, constraints, enabling framework	167
4.49	Technology Paper No. 49: CO ₂ use: Basic chemicals, urea, formic acid, polymers	168
4.50	Technology Paper No. 50: CO ₂ use: Power-to-gas (CH ₄)	170
4.51	Technology Paper No. 51: CO ₂ use: Power-to-liquids (Methanol)	172
4.52	Technology Paper No. 52: CO ₂ use: Enhanced Oil or Gas Recovery (EOR/EGR)	174
4.53	Technology Paper No. 53: CO ₂ use: Algae capture and fuel production, biofuels	176
4.54	Technology Paper No. 54: Natural Carbonation	178
4.55	Technology Paper No. 55: Enforced (re)carbonation/mineralisation	180
5	Annex I: Key assumptions	184
6	Annex II: Performance data of reference plant and cost figures used	185
7	Annex III: References	186
8	Annex IV: Definition of TRL (Technology Readiness Level)	217

1 Introduction

The global cement and concrete industry has embarked on a net-zero CO₂ transition which is the biggest transformation ever undertaken in this sector. It is beyond question that this transformation will require tremendous effort, but the cement and concrete producers are fully committed to making this enormous task a success and delivering net-zero CO₂ cement and concrete by 2050.

The sector has elaborated the different decarbonisation pathways which need to be implemented to decarbonise the cement and concrete value chain. On a global level, GCCA, the Global Cement and Concrete Association, has developed a roadmap for net-zero CO₂ by 2050. On a regional level, different roadmaps have been elaborated and numerous initiatives are aiming at localising and accelerating the necessary measures.

As this transformation towards net-zero CO₂ is so enormous, it is clear that an ongoing exchange among all participants along the value chain is necessary. Different roadmaps have addressed policy tasks which comprise the need for a coherent framework of regulations and supportive actions. It will be this joint effort of the sector, policy makers and all stakeholders from the cement, concrete and construction industries, as well as the involvement of society, which will make the journey towards net-zero CO₂ possible.

The cement industry has been working on technical solutions not only to make its processes energy efficient, but which will also allow the decarbonisation of clinker and cement. The ECRA Technology Papers summarise the different technologies and their impact on energy demand and CO₂ emissions. They show detailed operational costs as well as investment figures. They provide a unique set of documents which enable decision makers in their specific companies to outline their decarbonisation pathways and ultimately their roads towards net-zero CO₂.

This current update of the Technology Papers is part of a cooperation with MPP, the Mission Possible Partnership, an alliance of climate leaders focused on supercharging decarbonisation across the entire value chain of the world's highest-emitting industries in the next ten years. Together, ECRA and MPP have been engaged in a Sector Transition Strategy for the cement and concrete sector. As with other sectors in which MPP has worked, each Sector Transition Strategy defines an aggressive, industry-backed, net-zero pathway. It underlines what needs to happen over time to meet this trajectory. The goal is to secure commitments to action in the 2020s from critical stakeholders in the value chain.

The current ECRA Technology Papers provide clear technical guidance to implement the STS for cement and concrete. They underline the financial aspects of the different decarbonisation levers and cluster them in state-of-the-art documents, also addressing the maturity and the technology readiness levels of the different technologies concerned.

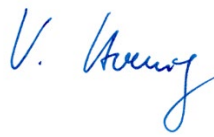
This update of the ECRA Technology Papers is based on previous Technology Papers. Already in 2009 ECRA addressed all relevant technical measures to lower CO₂ emissions from cement manufacturing. Commissioned by the Cement Sustainable Initiative (CSI) of the World Business Council for Sustainable Development (WBCSD), the 2009 Technology Papers were the basis for the IEA's Cement Technology Roadmap. In 2017 – again in a joint project with CSI – ECRA updated the Technology Papers to form a new basis for the Energy Technology Perspective (ETP) modelling project of the International Energy Agency (IEA).

The current update takes into account recent and future developments which are important for the sector on its transition towards net-zero CO₂ by 2050. These include the role of supplementary cementitious materials such as calcined clays, the different technologies for capturing CO₂ at the cement plant, and ways to recarbonate hardened cement pastes to permanently bind CO₂.

ECRA would like to thank MPP for its excellent cooperation and its open and constructive discussions at all times. Great thanks are also owed to GCCA, its management team and its members for their valuable input and support, but even more so for the spirit which GCCA has created within the sector to deliver net-zero CO₂ concrete by 2050. Finally, ECRA would like to thank the team of VDZ for its enormous support based on a deep understanding of the cement and concrete value chain, which has made the compilation of these updated Technology Papers possible.



Martin Schneider



Volker Hoenig



Johannes Ruppert

2 Key assumptions

The key assumptions, the terminology and definitions used, and the data of the reference plant are given in Annexes I, II and IV of this report. The most important assumptions are summarised as follows:

Reference plant

These Technology Papers provide figures for energy demand, CO₂ emissions, material inputs, operational costs and capital expenditures. As in the previous Technology Papers, these figures are given in comparison to a reference cement plant if not stated otherwise. Thus, the investment figures and the operational costs are given as the difference to the reference plant (“switch cost”).

Key indicators reference plant

The clinker capacity of the reference plant is 6,000 t/d, its CO₂ emissions 832 kg fossil CO₂/t clinker, the clinker cement factor 0.72, the thermal energy demand 3,352 MJ/t clinker, and the substitution rate of alternative fuels 6.4% (4% fossil-based and 2.4% biomass respectively). These key parameters were chosen according to those given as a global average for clinker and cement production in the GCCA roadmap for the year 2020. Further detail on the scope of assessment and any adjustments to the general reference are provided as specific remarks and conditions in each technology paper.

No inflation taken into account

All investment figures and operational costs refer to 2020 as the reference year. Since inflation is difficult to forecast and can be very different from region to region, no inflation has been taken into account. The approach chosen is in particular important for large investment projects such as carbon capture technology. As the projects will be completed many years in the future, the costs shown and investment figures are mainly to be used as a comparison between the different technologies.

Regional differences

Investment figures and costs for fuel, electricity and materials as drivers of OPEX can strongly vary from region to region, as is known from many projects. However, these Technology Papers aim at global average figures. They have been derived from public information, the 2020 ETP-modelling, the NZE by 2050 IEA Roadmap for the Global Energy Sector, ECRA’s own research, and interviews with industry stakeholders undertaken by ECRA.

CAPEX figures for capture projects

CAPEX figures for capture projects are given for the capture plant only. This allows for better comparisons between the capture technologies because site-specific investments are excluded such as onsite intermediate CO₂ storage, the upgrade of power supply, demolishing old equipment, water treatment, CO₂ logistics on site, and finally transport or storage. The uncertainties in investment figures for site specific investments can require up to 100% additional investment as compared to the figures for the actual capture plant.

While investment figures are a significant part of the overall expenditures the upcoming capture projects indicate that the total project costs can still be significant higher. This also takes into account that – depending on the capture technology and its TRL - first of a kind projects might require higher effort than those built after certain experience has been gained.

3 State of the art

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

Based on the GCCA database (the former CSI “Getting the Numbers Right” data collection) from 2019, the thermal energy demand for cement clinker manufacturing was 3,460 MJ/t cli (global weighted average for grey clinker, excluding drying of fuels). This figure covers 22% of the cement production worldwide and all technologies. The variation in thermal energy demand was from 3,000 MJ/t cli to 4,000 MJ/t cli given as the 10% percentile and 90% percentile respectively of all kilns covered. The highest energy demand is required for the wet production process (up to more than 5,400 MJ/t cli), while the lowest figures of around 3,000 MJ/t cli are achieved by state-of-the art precalciner kiln technology linked to large kiln capacity, low moisture content and good burnability of the raw materials. It has to be stressed that these data represent yearly averages, whereas performance figures are usually expressed as short-term (typically 24h- or 36h-average) figures. Depending on the kiln operation, its utilisation rate and the number of intermittent kiln stops, the short term performance figures are 150 to 300 MJ/t cli lower than the average annual thermal energy demand.

As cement manufacturing is capital-intensive, the lifetime of cement kilns is usually 30 to 50 years. While new kilns are typically built to adapt capacity to the respective market, existing kilns and their equipment are continually being modernised. This means that in practice the original equipment such as preheater cyclones, the clinker cooler or the burner has been almost completely replaced after 20 or 30 years and exhibits modern, state-of-the-art technology. This underlines that even though kilns might be relatively old, they nevertheless operate efficiently and according to latest environmental requirements.

Huge retrofits such as changing from wet to dry processing allow a significant step towards increasing energy efficiency. However, since for these kinds of retrofits a similar investment as for new kilns is required, a new kiln often is the preferred choice to close the efficiency gap between the old and state-of-the-art technology. In any case, the market demand is the overarching driver to adjust or replace existing technology.

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. This corresponds to a theoretical thermal energy demand of already 1,650 to 1,800 MJ/t cli. Depending on the moisture content of respective raw materials, a further energy demand of about 200 to 1,000 MJ/t cli (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 cli is set by chemical and mineralogical reactions and water evaporation. Furthermore, waste heat from the kiln exhaust gas, the bypass gas and/or cooler exhaust air is often used for the drying of the raw materials or other materials such as coal and petcoke, or cement constituents like granulated blast furnace slag. Also, the recovery of waste heat for electrical energy production in waste heat recovery processes contributes to energy savings and correspondingly high energy efficiency. Since most of the even low temperature waste heat streams are used, the overall 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 equally high-efficient since the heat utilisation for raw material drying or electric power generation 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, humidity)
- 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, because some measures or technologies have similar or sometimes even conflicting impacts. Secondly, it is not possible to go beyond the minimum energy demand, meaning that “one kJ can only be saved once”. It is important to highlight that many thermal energy reducing measures require additional electrical energy, which can be a conflict which has to be looked at in detail under the specific measures to be implemented.

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 GCCA data, the weighted average of the specific thermal energy demand for this kiln type in 2019 was 3,360 MJ/t cli. The respective figure for 1990 was 3,590 MJ/t cli, equivalent to a reduction of ca. 230 MJ/t cli over 29 years. In this time period the average kiln capacity increased significantly. While at the beginning of the 1990s maximum kiln capacities of 5,000 to 6,000 tpd were typical, today maximum capacities can reach from 8,500 to even more than 10,000 tpd. Although there are technical reasons why kiln sizes might be limited to around 12,000 tpd, the average kiln capacity of cement plants is expected to increase globally. New kilns tend to be built with higher capacities, not only in growing markets, but for efficiency reasons. Existing, smaller kilns tend to be replaced by larger ones whenever the local market situation allows for this, or the combining capacities of existing kilns is possible.

A study carried out by VDZ, Germany, in the context of the European BAT process has determined the ranges for the average yearly fuel energy requirement of state-of-the-art cement kilns based on theoretical modelling and empirical data. These data take all criteria and impacts into account. The number of cyclone stages reflects the need for sufficient waste heat after the preheater for drying or waste heat recovery if applied:

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

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

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

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

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 3,460 MJ/t cli in 2019 to a level of 3,300 to 3,400 MJ/t cli in 2030 and to 3,150 to 3,250 MJ/t cli in 2050.

However, without impairing efficiency, these specific energy data can be higher if additional waste heat has to be provided for the purpose of cogeneration of electric power. Similar considerations apply if Carbon Capture and Use or Storage (CCUS) is 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 or raw materials which require wet preparation.

3.2 State-of-the-art Paper No. 2: Electric efficiency of cement production: State-of-the-art and long-term perspective

Based on the GCCA database (the former CSI “Getting the Numbers Right” data collection) a global average electric energy demand for cement manufacturing of around 102 kWh/t cement was reported for the years 2014 to 2019. Since 2011 the electrical energy demand for cement production has remained constant. These figures represent around 23% of plants worldwide, and all technologies and clinker and cement types. The variations are significant: The 10% best in class show figures of 83 kWh/t cement and below, while the 90% percentile amounted to 140 kWh/t cement. 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, new assets have predominantly been installed in regions with high market growth. On the other hand, in many mature markets a trend towards higher product fineness, higher alternative fuel rates and an additional demand for secondary abatement technologies have increased energy demand. This has been compensated since 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 has always been adapted to modern technology. These counteracting developments lead to a more or less constant electrical energy demand. Since grinding makes up for around 70% of the total electrical energy demand for cement production, further significant steps in reduction of the specific energy demand will be possible through changing from cement grinding with ball mills (BM) to highly efficient vertical roller mills (VRMs) or high pressure grinding rolls (HPGRs). This investment however has to be seen against the background of the regional market development and the cement performance which can be different for the different grinding schemes.

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 and grinding, 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 – such as 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 improve 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. In addition, specific power consumption has also increased in many countries due to the use of alternative fuels and because of increased environmental obligations. Alternative fuels increase the air demand and thus the power demand of clinker production. 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 SO₂) requires additional units which need electricity. The use of SCR technology for NO_x abatement, for example, results in an increase in electrical energy demand of up to 10 kWh/t clinker.

Electrical energy demand cannot only be reduced by updating major equipment. Improving efficiency of auxiliary systems (especially compressed air) and replacing inefficient medium-size fans can at least provide minor power savings at short payback times.

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
- Emission abatement technologies applied
- Technical status of the plant
- Plant operation and flexibility of operation
- Technology for Carbon Capture and targeted CO₂ quality (purity and pressure)

The technologies and the 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 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 GCCA GNR data, the global weighted average of the specific electrical energy demand for all participating companies has not been reduced over the past 10 years. But as described above, continual technological renewal of existing plants, new installations and large retrofits in emerging markets have compensated the increasing energy demand arising from product fineness, alternative fuels and abatement technologies.

Grinding processes demand the majority of power during production, and in theory there are still significant savings potentials. It is well known that ideal single particle comminution requires much less energy than large-scale industrial grinding equipment being used today. But industrial grinding involves handling mass flows of up to 1,000 t/h, which limits the possibilities to focus grinding forces to individual particles. There are no real breakthrough technologies available today, but there is still significant potential to improve the implemented technology mix in order to further increase energy efficiency and limit the risk related to the substitution of existing equipment. This involves high pressure grinding, but also special fine grinding applications (like separate ultra-fine-grinding), which meet the requirements of today's product portfolios more efficiently.

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 and with respect to different costs for electrical power depending on the time of the day. By designing production facilities like grinding plants and silo capacity in such a way that equipment can be easily started and stopped for relevant time periods, production can be adapted to the transition of the energy market towards an increased use of renewable energy and to the spot-price of electricity. This will not reduce but rather slightly increase the absolute power demand, but reduce the indirect CO₂ emissions of power generation and the overall costs for electricity.

A large number of plants are still using equipment installed 30 to 50 years ago. In many cases today a retrofit of grinding plants is economically not feasible just through savings in electrical energy. But the above-mentioned requirements for the use of renewable energies as well as the further reduction of the clinker-cement-ratio will require larger grinding capacities for given kiln lines. It is therefore expected that equipment for cement grinding will be significantly updated over the coming decades.

With regard to the thermal process, it can be expected that environmental requirements will increase and that the cement manufacturing process therefore has to be enhanced by more and more units for emissions abatement (especially for carbon capture technologies, which are addressed in a separate Technology Paper), resulting in a significant increase in power consumption.

Based on these assumptions, the specific electric energy demand of cement production without carbon capture may decrease from 102 kWh/t cement in 2019 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.

As indicated above this estimate excludes new electricity-intensive technologies like carbon capture technologies (CCUS). If CCUS is applied on an industrial scale, the power demand of cement manufacturing will increase significantly. As described in the respective Technology Papers, carbon capture technologies will require high power consumption to e.g. supply consumables like oxygen, pump solvents, operate power driven separation devices like membrane or cryogenic units and purify and compress the CO₂ in order to meet the required conditions of downstream processes. Therefore, CCUS will increase power consumption by 50 to 300% at plant level.

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

The co-processing of wastes as alternative fuels and the use of alternative raw materials has a long tradition in the cement industry. However, the degree of using these materials in the cement production process varies from region to region. The average utilisation rate of alternative fuels and raw materials is still rather low on a global level. For example, the GCCA roadmap process has shown that on a global average around 6% of fossil fuels are replaced today by alternative fuels, roughly two thirds of which are fossil based, and roughly one third of which is of biomass origin.

From a technical point of view, much higher substitution rates are possible. Experiences in some European countries show substitution rates of more than 70% on average on a country level and up to 95% as a yearly average for single cement plants. As the fuel-related CO₂ emissions constitute about one third of the total emissions (302 of 838 kg CO₂/t cli - incl. biogenic CO₂ - for the reference plant), the CO₂ reduction potential through the use of alternative fuels can be significant, in particular if they contain biomass or if pure biomass is used. Besides these direct effects, the use of waste as alternative fuel in cement kilns may contribute to lower overall CO₂ emissions. The replacement of fossil fuels and their relevant CO₂ emissions by waste materials avoids emissions of these materials, which would otherwise have to be incinerated or land-filled with corresponding greenhouse gas emissions. This is particularly important since emissions from landfills consist of about 60% methane, a gas with a global warming potential 25 times that of CO₂. 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 CO₂ emissions from the de-carbonation of raw materials as well as CO₂ 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

Typical alternative fuels classified as wastes are waste tyres, waste oil and solvents, pre-treated 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 animal meal. Besides these fuels, many other organic waste materials are used as fuels in the cement industry globally, however to a smaller extent. Fuels containing biomass are mainly pre-treated industrial and domestic wastes containing certain parts of organic fibres and textiles or paper. In principle, it is also possible to use other organic materials as fuel, such as natural wood or certain grass types (e.g. miscanthus), other fast-growing species or cultivated green algae. However, today this is only of local relevance for the cement industry, mainly for economic reasons and because of limited availability.

In the coming years, the use of hydrogen – in addition to alternative fuels – can contribute to the reduction of fuel-related CO₂ emissions in the cement industry. When pure hydrogen is used as a fuel, only water (H₂O) is released instead of carbon oxides. Another advantage of using hydrogen in the cement industry is the high efficiency compared to other industries, as no process-related compression of the gas is required.

The biggest challenge is the availability of a sufficient amount of carbon neutral “green” hydrogen, and in particular carbon neutral electricity needed for its production. Currently, the use of hydrogen as a fuel in the cement industry is of no relevance. In the future, an average share of 10% hydrogen of the total thermal energy demand seems possible (see Technology Paper No. 18).

Raw materials

The local availability of suitable de-carbonated raw materials is often limited. Typical alternative raw materials are blast furnace slag, lignite ash, foundry sand, recycled concrete fines, carbide sludge, or lime residues from different industries. These materials may exhibit a significant CO₂ reduction potential depending on the de-carbonated fraction, which may vary strongly even for the same material, such as e.g. in the case of recycled concrete fines. Some materials can be used both as alternative raw materials for clinker production but also as SCMs in cement such as granulated blast furnace slag, fly ashes or pozzolana (see State-of-the-art Paper No. 4). Further preparation steps may be needed to improve the quality of the material. In particular, alternative raw materials from wastes may require careful testing with regard to their suitability for use in the clinker production process.

Alternative raw materials may also allow the optimising of the lime saturation factor (LSF). The respective savings in CO₂ emissions and energy are covered in Technology Paper No. 39.

Criteria

- In principle, cement kilns can utilise up to 100% of alternative fuels. Nevertheless, there are certain technical limitations, like their chemical composition, their calorific value, or their content of 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 65% of the fuel input is realised, the lower process temperature also allows the use of low calorific fuels. When low-calorific fuels are used as well as in cases when a by-pass is needed, the specific fuel energy demand will increase to a certain extent. However, also under these circumstances the use of alternative fuels results in a reduction of CO₂ emissions.
- The technical and operational experience in using alternative fuels is available within the cement industry, which is a major criterion as cement kilns operate differently at higher rates of substitution of conventional fuels with alternative fuels.
- Higher substitution rates will normally require respective waste management and waste legislation in the given region. Sometimes it is difficult to compete with landfills, and policies need to incentivise the valorisation of alternative fuels in cement plants.
- The social acceptance of using wastes as alternative fuels in cement plants is of relevance.
- For the use of separately grown biomass crops, the availability of agricultural areas, especially in densely inhabited regions, is of relevance.
- CO₂ legislation will have a significant impact on waste markets and the availability of biomass fuels for the cement industry.
- Hydrogen as an additional fuel requires sufficient carbon neutral electricity for its production.

- 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.

Expected market development

Cement producers not only contribute to a circular economy by using alternative fuels or raw materials, but can make economic benefit by substituting fossil fuels and conventional raw materials. Due to the different market prices and the contribution to energy and CO₂ savings in clinker production, alternative fuels and raw materials play an important role in the transition of the industry towards a net-zero CO₂ sector.

In the future it can be expected that cost for using alternative fuels and especially biomass will increase due to the overall market development and the need to process and pre-treat new waste streams accordingly. The benefit against fossil fuels, however, will remain, in particular when CO₂ costs are taken into account.

The utilisation of alternative calcium-containing raw materials (like blast furnace slag, lignite ash, concrete crusher sand, carbide sludge, aerated concrete meal or lime residues) which are already de-carbonated offers a chance to reduce CO₂ emissions. Nevertheless, the availability of such de-carbonated raw materials is often limited – or they are used as SCM in cement. In rare cases and depending on local availability, substitution rates up to the amount of 15% of the raw meal may be realistic.

Development of state-of-the-art techniques

It is very difficult to predict levels for the future substitution of conventional fuels by waste or biomass fuels due to the large number of economic, political and societal criteria described above. It has to be stressed that the achievement of higher substitution rates depends more on political and legal aspects than on technical ones.

Based on the GCCA roadmap, the substitution rate in 2050 is expected to be slightly above 40%, roughly two thirds of which will be fossil wastes and roughly one third of which will be biomass. Differences in substitution will remain between regions, based on existing waste markets, waste management systems and waste legislation.

3.4 State-of-the-art Paper No. 4: Reduction of clinker content in cement: Long term perspective

Based on the GCCA Roadmap data for the year 2020, the clinker-to-cement ratio on a global level was 72%. With a total cement production of about 4,200 Mio. t this was equivalent to the use of around 1,160 Mio. t of supplementary cementitious materials (SCM) substituting clinker. The variations of the clinker-to-cement-ratio in the different world regions were significant in 2020: An average clinker-to-cement ratio of 66% (2015: 57%) has been reported for China based on the use of significant amounts of fly ash and slag. In Europe, for example, the average clinker factor was 77%. Today, materials like blastfurnace slag, fly ash, natural pozzolanas or limestone meal are available globally in respective quantities, their regional availabilities are however very different. From a technical point of view, lower average values in the clinker-to-cement ratio are possible.

Materials which can substitute clinker in cement

Cements that contain SCM as other constituents besides clinker exhibit a lower clinker-to-cement-ratio than Portland cement and consequently show less overall CO₂ emissions per tonne of cement. SCMs can have 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 GBFS exhibits latent hydraulic behaviour. 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 exhibits a lower early strength if ground to the same fineness and a lower heat of hydration. On the other hand, 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 can be siliceous or calcareous and has pozzolanic properties. Therefore, silicious FA contain aluminosilicate phases which can react with calcium hydroxide formed by clinker hydration and contribute to strength development. 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 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 such as calcination. Other pozzolanic materials such as rice husk ash can also have particular local relevance. Silica fume, a by-product in the production of silicon and ferro-silicon alloys, is a very effective pozzolanic material because of its extreme fineness and its high silica content. However, its worldwide availability is very limited. All pozzolanas contain siliceous or aluminosilicate phases which can react in the hardening cement paste and contribute to its strength development. In comparison to Portland cement, the early strength of pozzolana-containing cements decreases with the increasing proportion of pozzolana.

They show a similar workability, a higher long-term strength and in particular an improved chemical resistance.

Limestone: The use of limestone as a constituent in cement is an efficient method to reduce the clinker content of cement. However, limestone does not significantly 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 and quality of limestone in cement as well as 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. Dolomitic limestones can also be used as a cement constituent if they have a sufficiently high carbonate content.

Recycled fines from mineral construction waste (recycled concrete fines) can be used in Portland composite cements as cement constituent. The amount can vary widely from 5 to around 20%, depending on standards or application rules. Portions of cement hydrate phases in the recycled fines that have not yet been carbonated can take up CO₂ by natural or enforced carbonation. Depending on the proportion of hardened cement paste, enforced carbonation can result in a significant pozzolanic effect and lead to a denser structure of the hardened cement paste. As a positive side effect of their use as an SCM, recycled fines can permanently bind additional CO₂ and preserve primary resources.

Recent developments use synergetic effects of optimised combinations of calcined clays and ground limestone as SCMs, allowing a clinker reduction of up to 50% and maintaining a similar performance to existing cements.

Criteria

The use of other constituents in cement besides clinker depends on different criteria:

- The availability, properties, and prices of the materials, the intended application of the concrete in which the cement is used, 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. In 2020, an estimated amount of 300 Mio. t/a GBFS was produced worldwide. In the context of global decarbonisation, pig iron production is to be increasingly shifted to Direct Reduced Iron-process (DRI) with hydrogen. This is expected to lead to a significant decline in the available quantities of slag. Findings on the properties of the resulting slag and its suitability as a cement component are not yet available.
- Fly ash (FA) is produced in coal-fired power plants. The worldwide production in 2020 was estimated at about 600 Mio. t, not all of which however is suitable for cement or concrete production. The future number and capacity of coal-fired power plants is very difficult to predict. But in the course of the increasing use of renewable energies, the number of coal-fired power plants and thus the availability of fly ash will also decrease significantly.
- Considerable resources of natural pozzolans such as trass or pumice, with a wide variation in reactivity can be assumed worldwide. Reliable data on the current worldwide production or which proportions are used as cement constituents are difficult to derive. As a rough estimation, the amount used for cement and concrete is probably around 20 Mio. t.

- Clays or shale as raw materials for natural calcined pozzolans are available worldwide in significant quantities. For cement production clays do not need the ceramo-technical properties which are required for brick or ceramic production. So far and on a global average, the volumes of cement being produced with natural and natural calcined pozzolans is rather low. However, due to their good availability, their lower CO₂ footprint as compared to clinker and their very good contribution to cement performance, these materials will have a great potential to replace granulated blast furnace slag and fly ash as well as clinker in future clinker-efficient composite cements.
- Limestone for clinker production is available for most cement plants, and will be available worldwide practically unlimitedly. As a general rule, limestone as a cement constituent must have a high carbonate content in order to be primarily frost-resistant. The availability of such pure limestones may be limited in some regions. Dolomitic limestones can also be used as cement constituent if they have a sufficiently high carbonate content.
- Waste concrete or other mineral construction waste as a source of recycled fines are usually available in large quantities. After crushing and separating of coarse recycled aggregates in processing plants, up to 30% fine material (< 2mm) usually remains, which can generally be used as recycled fines. Areas for processing and storage as well as the influence of additional transport efforts in the processing and to the cement plants must be taken into account.
- The **properties** of SCMs are very important and always have to be assessed with respect to the intended application of the cement. In general, the more reactive the material (hydraulic, latent-hydraulic, pozzolanic behaviour), the easier it is to substitute the clinker without significantly changing the cement properties. As a rule, the early strength decreases with decreasing reactivity of the cement components and the curing of concretes becomes more important. Furthermore, composite materials must not affect the technical properties and environmental compatibility of cement and concrete.
- The **prices** of SCMs depend on the local situation. They are predominantly determined by the regional availability and the costs to process and transport them.
- In addition to improving environmental efficiency, cements with SCMs offer the possibility of combining the advantages of the individual components. This enables an even more precise adaption of the concrete composition and properties to the expected requirements and allows a wide range of **application**. The increased use of such cements in mortar or concrete must always be ensured by appropriate workability and durability, adequate strength development, and, if necessary, sufficient resistance to aggressive media. For example, blast furnace cements can contain up to 80% or even 95% of GBFS. However, due to their low strength development these cements are only suitable for very special applications such as mass concrete or marine constructions. For most concretes, however, the requirements are less specific. This applies for example to interior components in which higher proportions of clinker can certainly be replaced by inert materials such as ground limestone. By lowering the concrete's w/c ratio, most of the disadvantages with regard to durability can be compensated for, so that even ambitious concretes can be produced with cements with a high limestone content. Difficulties in workability can be compensated by using plasticisers.

- The use of composite cements requires that cement and concrete **standards** and **rules** have to be revised. The testing methods under which cements and concretes have to prove their performance had originally been made for cements with higher clinker content than in tomorrow's clinker-efficient ones. This needs to be adapted while at the same time ensuring the use of concrete for safe and durable buildings and infrastructures.
- The **market acceptance** of clinker-efficient cements currently still depends mostly on the early strength of the cements. The ecological advantages of these cements (lower CO₂ footprint, resource-saving) will become more and more evident and will facilitate their acceptance. Cement and concrete manufacturers will have to make joint efforts together with planners, architects and construction companies to take advantage of these new carbon-efficient cement. This also includes a procurement scheme to take the CO₂ efficiency of cement and concrete more into account that has been done in the past.

Expected development of clinker reduction in cement

The increased use of calcined clays, natural pozzolans, ground limestone or recycled fines as SCMs will not only compensate for the decreasing quantities of fly ash and granulated blast furnace slag. These SCMs will also allow to further reduce the clinker factor in all regions. Average cement compositions with 8% to 16% calcined clays or natural pozzolans and up to almost 20 % limestone are partially predicted for 2050. A reduction of the worldwide clinker-to-cement-ratio to approx. 59% seems possible.

It has to be considered that in some countries such as China, the US and several European countries, SCMs are used as concrete additions based on the building traditions. The local standards apply and the CO₂ saving potential is the same as for the use of SCMs in cements.

While SCMs will play a growing role in tomorrow's cements, clinker will still be the most important cement constituent. There is no material in sight today which could replace clinker on a broad scale – with respect to the amount of clinker needed, the availability of sufficient raw materials to produce it, and with respect to its performance in concrete, which ensures safe and durable buildings and infrastructures.

Remark:

Estimations on the impact of SCMs on energy consumption, CO₂ reduction potential and costs of cement production in the corresponding Technology Papers No. 34 to 38 are based on a comparison to Portland Cement (clinker/cement ratio: 95%). Unless otherwise described, all other estimates are based on a comparison with an average generic cement (clinker/cement ratio: approx. 72%).

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

Alkali-activated binders

Suitable materials to produce alkali-activated binders are aluminosilicates, which can be of natural (natural pozzolana) or industrial origin (metakaolin, fly ashes, granulated blast furnace slags - GBFS). The global availability of these materials is limited and existing volumes of such aluminosilicates are currently being used as supplementary cementitious materials (SCMs) in cement and concrete production. The high sensitivity to different water contents makes alkali-activated binders difficult to use in ordinary concrete applications, especially since concrete aggregates often exhibit very different moisture contents, 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. To derive the CO₂ footprint of these materials, the contribution of the activators must be taken into account. 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 such as 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 but hardens by means of carbonation. Its non-hydraulic properties allow for easy transport and storage because it is insensitive to moisture. Water only enables a certain workability of the fresh concrete for casting and is mainly removed during CO₂ curing and 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 CO₂ rich atmosphere at ambient gas pressures serves as an effective CO₂ sink. Based on the today's global clinker-to-cement factor of 72%, the possible CO₂ savings potential is around 60% if the CO₂ produced during the clinker burning process is captured and reused for carbonation. Operational safety during working with CO₂ has to be assured. Therefore, such technology seems to be rather suitable for pre-cast plants near CO₂ emitters for the production of unreinforced precast elements. Concrete properties are adjustable via the composition and especially by the duration of CO₂-curing. Reportedly, concretes with up to 80 MPa with sufficient durability (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 synthesis of non-hydraulic calcium-hydrosilicates (CHS) 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. The essential raw materials, limestone and quartz, are globally available in great abundance.

One approach is the activation of autoclaved non-hydraulic CHS-precursors (e.g. α -C₂SH) phase by special grinding to hydraulic calcium-hydrosilicates (hCHS). These phases react with water to calcium-silicate-hydrates (C-S-H), contributing to strength development. The autoclave and activation-grinding process differs widely from the conventional cement manufacturing process. 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 – which does not generate Ca(OH)₂ - a matrix with a very low permeability is formed very early, which might be advantageous for high durability issues. A CO₂ saving potential between 30 and 50% compared to average Portland cement clinker is reported. Compared to average global cement composition (clinker-to-cement factor of around 72%) the saving potential might be correspondingly lower. Currently no real cost figures are available for such a procedure. A first industrial plant with a capacity of 50,000 t/a is planned for 2024/2025.

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 development of early strength 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 economic hurdle, as the heat from the clinker cannot be sufficiently recuperated with the currently known systems. Increased alkali contents might be a concern for Alkali Silica Reaction (ASR) in concrete.

The properties of concretes made with belite cements are well known. Concretes with belite cements exhibit a low water demand, an excellent workability and a dense microstructure (less portlandite) and high long-term strengths as well as a very moderate development of hydration heat. Compressive strength development can be significantly increased by heat treatment. Due to the relatively low strength development in combination with the relatively low CO₂ saving potential, such cements are only used for regionally-specific applications such as massive concrete structures or dams. Furthermore, the properties of concretes from belite cement can also be achieved by the use of conventional cements, in particular CEM III.

In countries that have been using belite cements for a long time, e.g. China, belite clinker as well combinations with other clinker types, e.g. CSA clinker, are expected to replace Portland cement clinker by up to 5% (see next section).

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 sulphate containing raw materials are necessary. The clinker can be burnt in conventional 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 (C_4A_3S) 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 (C_2S), 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 cementitious materials. Basically, comparable properties as known for Portland cement concrete can be adjusted. At present less than 2 Mio. t/a of CSA cements (CSA > 40%) are produced and used mainly in China for structural and non-structural concrete. The amount of produced BCSA cements (Belite > 40%) might be lower, while BCSA cements are mainly used for non-structural applications due to the lack of standards. 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 depend among other things on legal framework, standardisation processes, CO₂-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.

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

CO₂ capture and storage is an approach to CO₂ abatement by which CO₂ arising from large point sources such as industrial processes is captured and stored away from the atmosphere permanently. It is now widely acknowledged that because of the high degree of process-related CO₂ emissions, the capture and storage (or utilisation) of CO₂ from cement plants is required to achieve the goal of net-zero CO₂ emissions. In addition, the storage of biogenic CO₂ which also results from the combustion of biomass or many alternative fuels can result in negative emissions. This is referred to as bio-energy carbon capture and storage, abbreviated as BECCS. Carbon capture and storage is referred to as CCS and carbon capture and utilisation is referred to as CCU. In general terms both pathways are referred to together as CCUS.

The cement industry has been investigating the application of carbon capture technologies for more than 15 years. Various capture concepts have been looked at against the background of the dedicated conditions of cement manufacturing, and different technologies to capture CO₂ have since been developed. They are grouped into post-combustion, oxyfuel and other integrated processes. Although the capture methods exhibit different levels of technical maturity, the technical feasibility of carbon capture in the cement industry is proven from prototype up to demonstration tests.

Initially, when the first concepts of carbon capture technologies were being examined in the cement industry, technologies which had already reached a high TRL in other industries such as scrubbing with amines or calcium looping were adapted to the specific boundary conditions of cement production. Chemical absorption by amines, and in particular by monoethanolamine (MEA) had been extensively applied in industrial processes. It has also been proven to work on an industrial scale in the power sector. Today, MEA is the most mature solvent. Its application in CO₂ capture has a TRL of 8 to 9.

Among the different capture possibilities, post combustion technologies are the least complex ones with regard to their application in cement manufacturing. However, the need to further improve their energy efficiency leads to a further development of back-end solutions. Adsorption processes using physical bonding (like membranes, pressure swing adsorption (PSA), temperature swing adsorption (TSA) and cryogenic capture) are rapidly developing and could be available in the medium term. So far, they have not reached a TRL higher than 5 to 7.

The higher the CO₂ concentration when entering the capture unit, the more efficient the capture process is. This puts the focus on the development of integrated technologies enabling high CO₂ concentrations from the cement clinker production process to be captured. Oxyfuel technology, integrated Calcium-Looping and indirect calcination have shown to be proven on prototype and pilot scale with TRLs up to 7.

Several industrial scale projects have been announced to come into operation by 2030 or earlier, which will pave the way for commercialisation (TRL > 8). As the choice for an appropriate capture technology is very site specific, the cement industry will apply a mix of technologies.

Currently, the costs for CO₂ capture amount from 40 to 80 €/t CO₂ avoided. For first-of-a-kind capture plants these costs can be higher. However, it is expected that the CO₂ capture cost will decrease in the future according to the technical and scientific progress in capturing technology. The above figures do not include additional costs for CO₂ transport and storage, which have a significant impact on the total costs of the CCS chain, depending on the plant location and access to CO₂ transport and storage infrastructure.

CO₂ capture technologies

A variety of capture technologies can be applied to cement clinker production. These technologies differ in their maturity levels and also in their overall capture costs. The greatest difference between these technologies is their level of process integration. Strongly integrated technologies like oxyfuel, integrated calcium looping or indirect calcination lead to an overall change of the conventional kiln design and also require the kilns to be operated differently, while post-combustion capture does not interfere with the kiln operation.

All chemical post-combustion technologies have in common that CO₂ is bound by a sorbent, the regeneration of which requires thermal energy. Post-combustion technologies can be classified according to the interaction between the CO₂ molecules and the capture material as chemical (absorption) and physical separation (adsorption) processes.

The most advanced post-combustion technology is based on chemical absorption because operational experiences are available in the cement industry, and high abatement rates are achievable. To operate a full-scale application, the thermal energy amount for regenerating the solvent is today quite high. To lower this energy demand and the related capture costs, waste heat from the clinker burning process can be used to cover the additional energy required for desorption. However, the available thermal heat at the site depends mainly on the needs for drying purposes or other waste heat recovery, such as electricity co-generation.

Calcium looping is another chemical post-combustion technology. It relies on the cycling calcination and decarbonation of calcium oxide (mainly limestone used as sorbent), meaning that synergies can be generated because the deactivated sorbent can be used as an alternative raw material in the clinker burning process. If applied as a tail end process the overall process design leads to a significant amount of waste heat which can be used to generate additional electrical power. Another version includes the combination of the calciners of the capture plant and the cement plant, which envisages the reduction of additional thermal energy. This concept is highly integrated and uses raw material as a sorbent, which can also be used as kiln feed after its deactivation. The adsorption potential of raw material is smaller in comparison with pure limestone.

The energy penalty of physical adsorption processes can be lower than for chemical post-combustion technologies like amine scrubbing. CO₂ adsorption and desorption in a repeated cycling is forced by either temperature (temperature swing adsorption, TSA) or pressure (pressure or vacuum swing adsorption, PSA/VSA) imposed on solid materials, which are filled in different types of reactors. The technological readiness strongly depends on the specific sorbents. They are still under further development, in particular with respect to their sensitivity towards impurities, their CO₂ capture rate and their achievable CO₂ purity. Adsorption processes can be combined with cryogenic capture units. The cryogenic separation process makes use of differences in the boiling points of the flue gas components. The technology combination has been proven in other industrial applications such as H₂ production.

In the long term, membrane technologies can also be a candidate for post-combustion CO₂ capture at cement kilns if membranes with sustained high separation performance can be found and developed for industrial scale application. First pilot scale projects have recently been started in cement plants.

Oxyfuel technology is currently seen as one of the most energy efficient and economic candidate for CO₂ capture at cement kilns, although it also increases operational costs significantly. The use of oxygen instead of air in the cement kiln firing results in a comparatively pure CO₂ stream, which can be supplied to a CO₂ transport and storage infrastructure with less effort for purification.

Oxyfuel technology involves the use of traditional cement plant equipment and commercially available units, which makes the integration less complicated. The operation of crucial plant units (calciner, burner, cooler) has been tested on pilot scale and at high CO₂ concentrations in industrial surroundings (CEMCAP project), leading to a TRL of these single units of 7. Of most importance for the oxyfuel process is - from a technical point of view - the required reduction of false air ingress into the kiln system.

To reduce the technological complexity of the integration of new technologies on the conventional kiln system, separate indirect calcining is proposed to focus on capturing CO₂ from the calcination process only. The capture efficiency is high but still limited to 60-70% of the total CO₂ emissions from the clinker process. The LEILAC technology (Low Emissions Intensity Lime and Cement) involves an indirectly heated calciner, which allows the separation of CO₂ released from the raw material. In combination with other technologies such as the use of decarbonised or biomass fuels or electrical heating, production without CO₂ emissions could be achieved.

Photosynthesis in algae or the use of CO₂ in greenhouses can also be seen as direct CO₂ capture (and use at the same time). Overall, however, photo-catalytic reduction of CO₂ is today still at a pilot stage (TRL < 6), technically but also with regard to its potential to be scaled up to higher CO₂ volume streams.

The transport and storage of CO₂ in amounts which arise from industrial sources like cement production require a dedicated CO₂ transport and storage infrastructure. While technological solutions are proven in large scale storage projects, e.g. in the US, and in enhanced oil recovery (EOR) projects, the costs, the relevant legal framework (especially for cross border transport) and social acceptance have to be addressed for large scale industrial applications. The mapping of potential CO₂ storage sites and their capacities on a global level indicates sufficient storage capacity to allow the cement industry's process emissions to be taken up, at least over the time period of the next 50 to 100 years. For example, Norway will start its first injection of CO₂ from industrial sources into off-shore storage sites in 2024, as in the Northern Lights project. It is expected that around 200 Gt of CO₂ can potentially be stored in the territory of the North Sea.

Pipelines will be the only long-term solution to transport relevant amounts of CO₂ from industrial point sources to the storage sites. Depending on the local circumstances, in the short-term CO₂ transportation by ship or railway can play an important role. R&D and standardisation efforts for the planning and development of CO₂ pipelines as well as investigations into reusing existing pipelines for natural gas are advancing. Today's projects face transport and storage costs, which can amount to more than 100 €/t CO₂. It is expected that costs will decrease down to 60 €/t CO₂ based on a fully developed infrastructure.

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

CO₂ capture and utilisation is an approach to CO₂ abatement by which CO₂ arising from large point sources like industrial processes is captured and reinserted into a carbon cycle (Carbon Capture and Utilisation: CCU). Currently, CCU 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 CO₂ from any capture process. The cement and lime industry are being discussed as CO₂ sources for CCU due to the generation of unavoidable process CO₂ from the calcination process, originating from the raw material limestone. The carbon accounting for CO₂ reuse is subject to life cycle assessments, but also to accounting regulations, which are about to be developed. These regulations will define carbon cycles which are sustainable. At the same time, they must assure consistency with existing policies such as CO₂ trading schemes and must avoid double counting. Finally, these regulations will have to take into account the economics of CO₂ reuse, since there is a practical necessity to allow for a long-term business perspective of industrial CCU, in particular in cases where storage of CO₂ is not yet an option.

CO₂ is a very stable molecule and its reuse requires sufficient amounts of energy. Most commonly hydrogen is used as the reactive partner and it is clear that all energy required for the hydrogen generation must be from carbon-neutral sources – otherwise this option would result in a net increase of the CO₂ emissions.

For most reuse technologies a dedicated upstream CO₂ capture process has to be applied, producing a CO₂ gas stream with the required quality and purity. However, there are also technologies where the capture and reuse of CO₂ are integrated into one process step. Whether the use of CO₂ can be carried out on the same site or in the vicinity of the capture plant depends on various parameters such as the availability of a transport infrastructure for CO₂, hydrogen or renewable electrical energy. Furthermore, synergies of the capture process with the utilisation of CO₂ through heat integration can improve the overall efficiency of converting the CO₂.

Carbon use technologies

Currently enhanced oil and gas recovery (EOR, EGR) is the most important utilisation of captured CO₂. It is state of the art in the oil and gas industry and it is economically viable, depending on the oil and gas price and CO₂ costs. The objective is not only to enhance the oil or gas production by the injection of CO₂ (tertiary recovery) but also to store CO₂ in cases where this has been captured as part of the oil and gas production process itself.

To reduce the need for traditional fossil carbon resources as feedstock in the chemical industry, carbon-based chemical products and fuels can make use of CO₂ captured from industrial sources or from the atmosphere. The participation of the cement industry in creating such sustainable carbon cycles will be an important option for cement plants in addition to storage sites and also requires a respective CO₂ transport infrastructure.

There are no principle technical limits for the reuse of captured CO₂ in chemical reactions with hydrogen (hydrogenation) to produce products like fuels, basic chemicals, polymers, etc. The hydrogen in most cases has to be produced by water electrolysis using carbon-neutral electrical energy.

Oxygen as a second reaction product of the water electrolysis could be used for an oxyfuel capture process in a cement kiln and several projects propose to use this in synergy.

The production of methane by CCU belongs to the so-called power-to-gas (PtG) concept. In the case of liquid reaction products (methanol, hydrocarbons, carboxylic acids, etc.) it belongs to a power-to-liquids (PtL) concept. A more general name subsuming the different options for catalytic reactions between CO₂ and H₂ is power-to-X (PtX). These and other options for the production of basic chemical products from captured CO₂ as an alternative source of carbon as a raw material, the technical feasibility of production processes at large scale, significant energy requirements and the economics are currently the subject of intensive research.

For large and long-distance transports, where it is not yet feasible to switch to electrified engines, hydrogen motors or fuel cells, the production of synthetic fuels is being discussed as a key CCU technology for fast reduction of CO₂ emissions and avoiding the use of oil and gas as fossil resources. The capture of CO₂ and its reuse for the production of fuels could become an interesting approach for the storage of excess energy from renewable sources. Although, the fuels deliver CO₂ again as a combustion product, the total CO₂ emissions will - from a life cycle point of view - be significantly 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. Concepts for synthetic fuel production often focus on dedicated supplies for aircrafts, ships and trucks in rural areas. A complete life cycle assessment for CCU for the generation and use of synthetic fuels should encompass the energy demand, energy use efficiency and remaining CO₂ emissions to the atmosphere.

Mineral carbonation, which is the reversed process of calcination, happens in a natural and slow way, but can also be enforced as a way of storing and utilising CO₂ from the clinker production. More on the different types of re-carbonation can be found in the state-of-the-art paper No. 8. Another example of CCU for the production of a chemical compound is the so-called Skymine process. Further details are described in the context of mineral carbonation (see Technology Paper No. 48).

The reuse of CO₂ 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 CO₂-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 can be used e.g. as animal feed. 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 constraint is however the huge space requirement of the algae farms.

It has to be mentioned that in addition to the discussed reuse options, other technological pathways are also being investigated such as electrochemical or biochemical conversions. However, these technologies are in early stages of development and exhibit a lower technical readiness level.

There are also small markets for the use of pure CO₂ gas streams in the food sector, for dry ice production or as supercritical solvents, etc. A combination of many versatile sales markets can lead to the generation of added value to otherwise unavoidable CO₂ emissions.

Criteria

- Hydrogen or electrical power based on carbon neutral energy resources, including appropriate infrastructures for scaling of CCU processes
- Infrastructure for linking CO₂ sources and processes using CO₂
- Economics strongly depend on revenues from the CCU products
- Establishment of new value chains for CCU and a respective carbon management
- Regulatory and legal framework for carbon accounting

Expected development of carbon use

The technological readiness (TRL) level and its ongoing progress is very different depending on the targeted chemicals or fuels. Some processes are already being applied commercially. In general terms, a wide range of the TRL from 4 to 9 can be indicated for relevant technologies from a 2022 perspective.

Most of the utilisation technologies are in an early stage of development so that cost numbers are difficult to estimate. In general, all reuse technologies have a significant demand for carbon-neutral energy. The cost of this energy and the revenues of the CCU products will be important factors to make CCU economically viable.

Today it is very difficult to predict how the different CO₂ reuse technologies will develop over the next decades. Much depends on the political framework and establishment of favourable conditions for CCU. This refers to the regulations on sustainable carbon cycles, energy taxes and duties, the availability of carbon neutral energy at a competitive price, and an established carbon price. Factors like the consumer's willingness to pay for a certain product and the environmental benefit of using CO₂ as a carbon resource also play an important role in the competitiveness of CCU.

3.8 State of the art Paper No. 8: (Re)carbonation: Long term perspective for the cement and concrete value chain

Carbonation is the formation of calcium carbonate from calcium-containing hydration products in the hardened cement paste of concrete. In this process, calcium silicate hydrate (CSH) phases and portlandite ($\text{Ca}(\text{OH})_2$) react with CO_2 to calcium carbonate and the pH value drops to below 9. The rate of natural carbonation is low in normal concrete under ambient conditions. Usually only a few centimetres of the concrete cover are affected by carbonation during the lifetime of concrete. Thus, a dense concrete cover protects the reinforcing steel from corrosion and ensures durable reinforced concrete elements. During its use, concrete on average takes up an amount of CO_2 equivalent to 20% of the respective CO_2 emissions from clinker production, leaving a remaining carbonation potential of about 80%. The carbonation of cementitious materials is recognised and considered as a CO_2 sink, as the Intergovernmental Panel on Climate Change (IPCC) has stated in its report of August 2021. Various model approaches exist, which predict different degrees of CO_2 incorporation depending on the assumptions being made and the model input data being used. Theoretical CO_2 absorption quantities can be calculated for hardened cement pastes and concrete elements (see Technology Paper No. 54). In principle, the same amount of CO_2 as is released from limestone during clinker production (calcination) can be completely re-integrated into the hardened cement paste.

Carbonation can be enforced when exposing hardened cement paste to humid atmospheres of high CO_2 concentration (see Technology Paper No. 55), aiming to bind as much CO_2 as possible in a short time. While very little CO_2 can be bound in fresh concrete, significant amounts of CO_2 of up to 35 mass-% related to cement can be bound during the enforced carbonation of concrete products after demoulding. Such high CO_2 uptake rates are not only due to the carbonation of hydrate phases and portlandite, but also to the carbonation of parts of the unhydrated calcium silicates. This type of enforced carbonation is currently used on a limited scale in a few countries such as China or India.

More common in the production of unreinforced concrete elements such as pavers is the carbonation of the upper millimetres of the concrete surface by a short CO_2 treatment in a CO_2 -chamber in order to effectively reduce the efflorescence tendency of concrete products.

Cement paste in crushed concrete or in recycled concrete fines has a high carbonation potential and can be almost completely carbonated relatively quickly. With appropriate moisture and CO_2 conditions, fine-ground hardened cement paste can be carbonated to around 80% after about 15 minutes and nearly completely after a 2 hours' treatment. Due to the carbonation of calcium silicate hydrates and calcium silicates, amorphous silicates with a pozzolanic reactivity remain. Fine ground, carbonated cement paste can be used as an SCM in composite cements. First standards have been developed such as EN 197-6 on a European level.

In principle, industrial systems for the carbonation of crushed concrete or hardened cement paste and for concrete product treatment already exist, such as curing chambers with steam and/or CO_2 . Nevertheless, enforced carbonation of crushed concrete or hardened cement paste is not yet being operated on an industrial scale. First pilot projects exist. Some further development is necessary to adapt existing systems to enforced carbonation.

Expected development of (re)carbonation

Enforced carbonation of hardened cement paste has the potential to be a promising CCU technology for the cement industry and could be a key element combining the decarbonisation of cement and concrete and its contribution to a circular economy. On the one hand, CO₂ emitted from clinker production can be incorporated, and on the other hand, the material produced can be used as a possibly pozzolanic cement constituent to reduce the clinker factor (see Technology Paper No. 40).

A challenge is certainly the large quantities of material to be handled. For one tonne of hardened cement paste, theoretically about 5 t of crushed concrete has to be processed. The efficient and effective separation of crushed concrete from the construction and demolition waste has to be further developed. Also, the separation of the hardened cement paste from the aggregate must be further improved. For further processing appropriate interim storage areas are needed as close as possible to the demolition site or the cement plant in order to minimise transports. The CO₂ treatment process should be designed for a high throughput of crushed concrete and concrete fines to ensure a high CO₂ uptake with the shortest possible retention times. For a direct use of flue gases from cement kilns for CO₂-treatment, local proximity between the waste concrete processing and the cement plant would be of great advantage.

Compared to the existing recycling practice for concrete, enforced carbonation requires as much concrete as possible which has to be collected for recycling, such as the reuse of crushed concrete components for the production of new fresh concrete (recycled aggregates) or for the cement production (recycled hardened cement paste as an SCM).

For all CO₂-treatment systems, the highly corrosive effect of the resulting carbonic acid on metal elements must be taken into account.

A special form of hardening via the carbonation of unhydrated calcium silicates such as e.g. Wollastonite is described in Technology Paper No. 44.

4 Technology papers

4.1 Technology Paper No. 1: Improving raw mix burnability e.g. through mineralisers

Certain constituents which are contained in the raw material or are added to the raw material mix to promote clinker formation can have an important influence on the burning behaviour. 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. In this respect 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 the sintering temperature of 200 K may result in a saving of fuel energy of up to 5%. Fluoride contents of up to 1% 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% mass-% of calcium fluoride (CaF_2) lowers the dissociation temperature of calcium carbonate, resulting in a total reduction potential of up to 180 kJ/kg cli. However, the saving potential of this measure is limited. Although the addition of small quantities of mineralisers can improve product quality, larger quantities will affect quality and the kiln operation through increased coating formation.

Additional costs of mineralisers and/or fluxing agents need to be considered carefully. The most frequently used CaF_2 is especially cost intensive and fuel savings usually do not outweigh the additional costs. However, if alternative raw materials containing fluoride are used, the impact on production costs can be positive. In general, however, the availability of such materials is limited.

Impact on energy consumption

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

CO₂ emission reduction

direct:	decrease of 4 to 16	kg CO ₂ /t cli	indirect:	increase of up to 0.6	kg CO ₂ /t cli
---------	------------------------	---------------------------	-----------	--------------------------	---------------------------

Material input

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

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Chemical properties, mineralogy and fineness of the raw mix and mineralisers/fluxing agents
- Impact on clinker quality
- Raw mix control and kiln feed homogenisation
- CO₂ intensity of fuel mix

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	0.09 to 0.56 decrease	not applicable	0.09 to 0.50 decrease
2030	not applicable	0.08 to 0.56 decrease	not applicable	0.08 to 0.56 decrease
2050	not applicable	0.10 to 0.56 decrease	not applicable	0.10 to 0.56 decrease

Remarks:

- Impact on 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.
- All other technical and financial assumptions been made are given in Annex I of this document

Conditions, barriers, constraints, enabling framework

- Costs 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

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

The dry process with cyclone preheaters and precalciner is the state-of-the-art technology for cement clinker production. Nevertheless, many long dry or long wet kilns still exist worldwide 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.

A long wet or long dry kiln does not have a preheater or precalciner, a reason why its energy consumption is comparatively high. For long wet kilns - due to the energy required for water evaporation - it can be up to 6,000 MJ/t clinker. A retrofit of a long wet or long dry kiln to a multi-stage preheater or a kiln with precalcining technique may be a feasible, but expensive measure for reducing energy consumption.

Energy savings through a retrofit depend strongly on the specific energy consumption of the existing kiln as well as the number of cyclone stages to be installed. These savings can range from 900 MJ/t for a long dry kiln and up to 2,800 MJ/t clinker for a long wet kiln, both in comparison to a modern preheater system with precalciner and a modern clinker cooler. A new preheater increases the precalcination of the raw meal before entering the kiln inlet with the consequence of the throughput of the kiln to be increased or to be doubled. Typically, the kiln length may be shortened which reduces radiation losses and refractory lining as well as 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 a 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 consumption

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

CO₂ emission reduction

direct:	decrease of 80 to 250	kg CO ₂ /t cli	indirect:	decrease of up to 2.8	kg CO ₂ /t cli
---------	--------------------------	---------------------------	-----------	--------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Initial specific fuel energy consumption of the long kiln
- Life cycle of the quarry
- Raw material humidity and number of cyclone stages
- Throughput capacity
- CO₂ intensity of alternative fuels
- CO₂ intensity of external power consumption

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	70 to 100	2.81 to 9.07 decrease
2030	not applicable	not applicable	70 to 100	2.81 to 9.10 decrease
2050	not applicable	not applicable	70 to 100	2.79 to 8.97 decrease

Remarks:

- The cost estimation for the retrofit cannot be based on a clinker capacity of 2 million 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 useful or required in conjunction, e.g. modernisation of the grate cooler or the introduction of alternative fuels (Technology Papers No. 8 and 14). Depending on the specific situation, the construction of a new kiln line within the existing infrastructure may therefore be more feasible. The mentioned change in operational costs include only fuel and power savings. Saving potential may be less if raw materials with very good grindability (e.g. chalk) are used.
- All other technical and financial assumptions been made are given in Annex I of this document

Conditions, barriers, constraints, enabling framework

- Very high investment costs incur with this measure
- Economics are ruled by fuel, power and CO₂ price
- Possible capacity increase depends on the potential of throughput increase of single installations (e.g. cooler, raw mill, cement mill)
- Economics can be improved by replacing primary fuels with alternative fuels

4.3 Technology Paper No. 3: Preheater modification through 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. Installing state of the art cyclones with lower pressure drop therefore reduces 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 of electric energy can be saved depending on the efficiency of the fan. While for most existing kilns of older type this amounts to savings of 0.6 to 1.5 kWh per ton clinker, savings of 3 kWh/t cli and 4 kWh/t cli have been reported in two U.S. cement plants.

Furthermore, a better distribution of solid material and the gas phase may result in an improved heat exchange. At a 3,000 t/d plant, a reduction of heat consumption by 25 MJ/t cli has been reported for a replacement of common top cyclones with counter-current cyclones. Electrical power savings were in the above-mentioned order of magnitude of 0.85 kWh/t cli. However, the lower pressure drop allowed a production increase of 5%, which decreased the specific electricity savings and increased the specific thermal energy savings to 0.34 kWh/t cli and 33 MJ/t cli.

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 consumption

thermal:	decrease of up to 33	MJ/t cli	electric:	decrease of up to 1.5	kWh/t cli
----------	-------------------------	----------	-----------	--------------------------	-----------

CO₂ emission reduction

direct:	decrease of up to 3	kg CO ₂ /t cli	indirect:	decrease of up to 0.8	kg CO ₂ /t cli
---------	------------------------	---------------------------	-----------	--------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Efficiency and volume flow of the ID fan
- The need for extra capacity influences energy saving / CO₂ reduction potential
- Temperature/number of cyclone stages
- Pressure drop and efficiency of existing cyclone stages before modification and actually achieved parameters
- Power price
- CO₂ intensity of (external) power generation

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	8 to 10	up to 0.20 decrease
2030	not applicable	not applicable	8 to 10	up to 0.21 decrease
2050	not applicable	not applicable	8 to 10	up to 0.19 decrease

Remarks:

- The investment cost estimation is based on a clinker capacity of 2 million 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 is based on the saving potential for a 3,000 t/d kiln as described above and includes the saving of electricity costs. Actual operational costs may vary significantly due to site-specific conditions.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- The rework is dependent on the situation of basement and tower structure of the preheater
- The use of exhaust gas fans with adjustable speed drives may optimise the process

4.4 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 raw material type, geographical location and season. Worldwide it can vary in a range of minimum 2 to 3% mass-% and in certain cases exceed 20% mass-%. The temperature and therefore the enthalpy in the kiln exhaust gas strongly depend on the number of preheater cyclone stages. A 6-stage preheater/precalciner plant using fossil fuels shows exhaust 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 is 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 60°C), which may allow for the addition of an extra cyclone stage. As the upper cyclone stage is normally designed double string (for better dust separation), at least two stages of the preheater 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 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 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 consumption

thermal:	decrease of 80 to 100	MJ/t cli	electric:	not available, increase possible	kWh/t cli
----------	--------------------------	----------	-----------	-------------------------------------	-----------

CO₂ emission reduction

direct:	decrease of 7 to 9	kg CO ₂ /t cli	indirect:	not available, increase possible	kg CO ₂ /t cli
---------	-----------------------	---------------------------	-----------	-------------------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Raw material moisture content
- Site conditions (free space, material supply, statics of preheater tower)
- CO₂ intensity of the fuels
- Additional power demand due to increased pressure drop - may be limited if low pressure drop cyclones are installed

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	5 to 8	0.25 to 0.31 decrease
2030	not applicable	not applicable	5 to 8	0.25 to 0.31 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 beyond the numbers given. Against this background, additional electricity costs may be neglected, provided that low pressure drop cyclones are used.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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 on a low level already
- Technology is only applicable to dry preheater kilns
- Technology is in competition with waste heat recovery

4.5 Technology Paper No. 5: Increase of kiln capacity

As the clinker-specific energy requirement is directly dependent on the dimension of the clinker kiln, an increase of the kiln capacity is linked to a reduction of specific CO₂ 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 specific electric energy demand (e.g. for fans). Investment in capacity increase can be an economically viable solution in growing markets or if two (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 CO₂ 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.

A simulation study has shown 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 CO₂ emission reduction, such as a modern multi-channel burner to fire high rates of 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 cli 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. Also, the level of capacity increase can be limited by the local availability of limestone.

Impact on energy consumption

ther- mal:	decrease of 150 to 200	MJ/t cli	electric:	decrease of 2 to 4	kWh/t cli
---------------	---------------------------	----------	-----------	-----------------------	-----------

CO₂ emission reduction

direct:	decrease of 13 to 18	kg CO ₂ /t cli	indirect:	decrease of 1 to 2.3	kg CO ₂ /t cli
---------	-------------------------	---------------------------	-----------	-------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Technology used for new installation (state-of-the-art)
- Plant efficiency
- Local conditions (size of limestone deposit, raw meal and clinker properties etc.)
- Thermal substitution rate
- 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]
2020	up to 290	0.55 to 0.83 decrease	not applicable	not applicable
2030	up to 290	0.6 to 0.9 decrease	not applicable	not applicable
2050	up to 290	0.58 to 0.86 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 only power and fuel saving. Labour and maintenance are not included in the operational costs.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- High investment costs
- Sufficient raw material deposit
- Legal and environmental conditions

4.6 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 for transporting the fuels and to stabilise the flame with swirl and axial air. 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 air ratio is reduced by replacing e.g. a mono-channel burner with 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.

Mono-channel burners are basically a refractory-lined single pipe with a nozzle, often used in kilns equipped with direct firing (the burners are in direct compound operation with the coal mill). 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 air volume flow. While mono-channel burners need primary air ratios of 20 to 25%, 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 emissions 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 consumption

thermal:	decrease of 25 to 37 for a precalciner kiln	MJ/t cli	electric:	no significant impact	kWh/t cli
----------	---	----------	-----------	-----------------------	-----------

CO₂ emission reduction

direct:	decrease of 2.2 to 3.3	kg CO ₂ /t cli	indirect:	no change	kg CO ₂ /t cli
---------	------------------------	---------------------------	-----------	-----------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Reduction of primary air ratio and recuperation efficiency of clinker cooler
- CO₂ intensity of fuel mix

Remark:

The impact on the energy demand is related to a comparison of a modern multi-channel burner with a mono-channel burner in direct compound operation with the coal mill, and both firing 100% coal in a precalciner kiln. Energy saving can be doubled for a preheater kiln.

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicabe	not applicabe	0.5 to 0.66	0.07 to 0.11 decrease
2030	not applicabe	not applicabe	0.5 to 0.66	0.08 to 0.12 decrease
2050	not applicabe	not applicabe	0.5 to 0.66	0.08 to 0.12 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 burner is taken into account
- Energy saving is lower in precalciner kilns
- Operational costs include absolute fuel cost only
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.7 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 containing biomass. Experience with oxygen enrichment has shown a reduction of specific energy demand by up to 5%, which results in a respective reduction of the CO₂ emissions.

By the use of additional oxygen, the nitrogen fraction of the combustion gas is decreased, thus less combustion air has to be heated up as compared to conventional combustion with ambient air. Consequently, the adiabatic flame temperature rises and the flame becomes shorter and brighter. The degree of oxygen enrichment is limited due to potential damage to the kiln refractory and due to potentially higher NO_x emissions because of an increase in thermal NO_x formation in the sintering zone. However, some research projects in the field of oxygen enrichment have been conducted in the past years, and 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 vol.-% in the combustion air has been reported. Other experiences show that under certain conditions oxygen enrichment is limited to an oxygen concentration of 23 to 25 volume% in the combustion air. Oxygen enrichment has not been applied to reduce CO₂ emissions so far, but the use of enriched combustion air may result in fuel savings and thereby avoids CO₂ 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 electrical power consumption.

Impact on energy consumption

thermal:	decrease of 100 to 170	MJ/t cli	electric:	increase of 10 to 35	kWh/t cli
----------	---------------------------	----------	-----------	-------------------------	-----------

CO₂ emission reduction

direct:	decrease of 9 to 15	kg CO ₂ /t cli	indirect:	increase of 6 to 20	kg CO ₂ /t cli
---------	------------------------	---------------------------	-----------	------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

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]
2020	5.5 to 11	increase of 0.4 to 1.9	5.5 to 11	increase of 0.4 to 1.9
2030	5.5 to 11	decrease of 0.4 to 2	5.5 to 11	decrease of 0.4 to 2
2050	5.5 to 11	decrease of 0.3 to 1.6	5.5 to 11	decrease of 0.3 to 1.6

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 is 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
- 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. This scenario was not included in the cost assessment above
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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

4.8 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. The 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 can be used for drying purposes, power generation or for heat generation which can be used in heating nearby buildings.

Important advantages of grate coolers compared to planetary or rotary coolers are:

- The larger capacity (up to 15,000 tpd) compared to max. 4,000 tpd
- The more efficient heat recovery

Principally, planetary or rotary coolers can be replaced by grate coolers. Modern reciprocating or walking floor grate coolers can be operated with extended lifetime and less heat losses. Grate coolers (and rotary coolers) can provide the precalciner with preheated tertiary air. Existing grate coolers with a typical efficiency of 50 to 65% can be optimised by adding a static first grate and – depending on the cooler type – a new grate with a modified aeration system. Depending on the housing condition 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 were developed with regard to better air distribution for reduced cooling air requirement, an effective conveying system for better transport of clinker with reduced clinker fall-through and clinker riddling, better modularity, mechanical stability of the cooler, optimum under-grate pressure. Compared to planetary or rotary coolers, heat recovery with grate coolers requires additional electrical power of approximately 1 to 10 kWh/t cli. 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 cli. 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 consumption

thermal:	decrease of 100 to 300	MJ/t cli	electric:	increase of 1 to 10	kWh/t cli
----------	---------------------------	----------	-----------	------------------------	-----------

CO₂ emission reduction

direct:	decrease of 9 to 27	kg CO ₂ /t cli	indirect:	increase of 1 to 6	kg CO ₂ /t cli
---------	------------------------	---------------------------	-----------	-----------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Throughput of clinker
- Requirement of tertiary air for 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]
2020	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.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Economics may not be viable because the market situation does not allow capacity increase
- Waste heat from cooler exhaust air can be used 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

4.9 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 might be 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, electric power production or heat recovery for other purposes such as district heating. 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 and 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 up 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 physical and chemical 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 with a respective increase in investment figures. 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 and 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. A few WHR boilers have been implemented in Europe, but high project costs are still the main barrier.

Depending on the chosen process and kiln technology, 8 to 10 kWh/t clinker can be produced from cooler exhaust 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 consumption

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.

CO₂ emission reduction

direct: 0 kg CO ₂ /t cli	indirect: decrease of 5 to 12 kg CO ₂ /t cli
-------------------------------------	---

Material input

not applicable

Technical Readiness

Technology Readiness Level (TRL): 9

The main influencing parameters are

- No direct CO₂ emission reduction, indirect reduction depending on CO₂ 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: CO₂ intensity of fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cli]
2020	20 to 30	0.5 to 1.5 decrease	20 to 30	0.5 to 1.5 decrease
2030	20 to 30	0.6 to 1.6 decrease	20 to 30	0.6 to 1.6 decrease
2050	20 to 30	0.5 to 1.3 decrease	20 to 30	0.5 to 1.3 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 primarily include power saving.

- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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/CO₂ price
- Clinker cooler technology: only grate coolers can provide waste air for heat recovery
- Efficiency is limited by a low waste heat temperature level
- Efficiency can be improved by using other media (organics, NH₃)
- 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 man-power

4.10 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 might be 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, electric power production or heat recovery for other purposes such as district heating. 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 up 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.

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 22%. 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 8 and 15 kWh/t cli can usually be produced by using ORC technologies.

Impact on energy consumption

thermal: 0 MJ/t cli	electric: decrease of 8 to 15 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.

CO₂ emission reduction

direct: 0 kg CO ₂ /t cli	indirect: decrease of 5 to 8 kg CO ₂ /t cli
-------------------------------------	--

Material input

not applicable

Technical Readiness

Technology Readiness Level (TRL): 9

The main influencing parameters are

- No direct CO₂ emission reduction, indirect reduction depending on CO₂ 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: CO₂ intensity of fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	15 to 25	0.5 to 1 decrease	15 to 25	0.5 to 1 decrease
2030	15 to 25	0.6 to 1.1 decrease	15 to 25	0.6 to 1.1 decrease
2050	15 to 25	0.5 to 0.9 decrease	15 to 25	0.5 to 0.9 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 primarily power saving.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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/CO₂ price
- Clinker cooler technology: only grate coolers can provide waste air for heat recovery
- Efficiency is limited by a low temperature level
- Minimum kiln capacity is needed

4.11 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 might be 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 electric power production or heat recovery for district heating. 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 up 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 NH₃. Kalina technology uses NH₃ as a cycling media which evaporates at lower temperatures and can therefore produce electric power at a temperature level at which steam turbines cannot 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 are 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 24 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 aimed at the minimisation of unused waste heat.

Impact on energy consumption

thermal: 0 MJ/t cli	electric: decrease of 10 to 24 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.

CO₂ emission reduction

direct: 0 kg CO ₂ /t cli	indirect: decrease of 6 to 14 kg CO ₂ /t cli
-------------------------------------	---

Material input

not applicable

Technical Readiness

Technology Readiness Level (TRL): 9

The main influencing parameters are

- No direct CO₂ emission reduction, indirect reduction depending on CO₂ 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 cem]	Investment [Mio €]	Operational [€/t cli]
2020	20 to 30	0.7 to 1.6 decrease	20 to 30	0.7 to 1.6 decrease
2030	20 to 30	0.7 to 1.7 decrease	20 to 30	0.7 to 1.7 decrease
2050	20 to 30	0.6 to 1.4 decrease	20 to 30	0.6 to 1.4 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 primarily power saving.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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/CO₂ 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 a combined gas and steam turbine or by co-firing additional fuels
- Minimum kiln capacity is needed
- Cost of additional man-power

4.12 Technology Paper No. 12: Alternative decarbonated raw materials for clinker production

The utilisation of alternative calcium-containing raw materials which are already de-carbonated offers a chance to reduce CO₂ emissions. This is a two-fold chance since process-related CO₂ emissions from the de-carbonation of the raw materials as well as CO₂ 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 to match the composition required for the clinker to be produced. In many cases, an excess amount of silica, alumina, magnesia or sulphur in alternative de-carbonated raw materials limits its large-scale utilisation. Also, the content of VOC or trace elements and a variable composition cause further restrictions in some cases. Furthermore, the availability of such de-carbonated raw materials is often limited. Further preparation steps such as in the case of concrete crusher sand, may improve the quality of the material but also increase the costs and the environmental impacts of the material supply. The following ranges are determined on one hand by the fact that the local situation may allow not or only a very limited use of alternative de-carbonated raw materials. On the other hand, the use of blast furnace slag may be realistic up to the amount of 15% of the raw meal in rare cases. The utilisation of an even higher amount is in principle possible but seems to be unrealistic due to the decreasing availability of blast furnace slag 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 consumption

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

CO₂ emission reduction

direct: decrease of up to 100 kg CO ₂ /t cli	indirect: increase of 0 to 2 kgCO ₂ /t cli
---	---

Material input

blast furnace slag	0.15 to 0.2 t/t cli
--------------------	---------------------

Remarks:

The calculations were made for a raw material replacement of 10 to 15% by blast furnace slag, which must not necessarily be granulated, such as for its use as cement constituent. Similar consideration can be made for other alternative de-carbonated materials.

Technical Readiness

Technology Readiness Level TRL 2022: 9

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 cem]	Investment [Mio €]	Operational [€/t cem]
2020	0 to 6	0 to 1 decrease	0 to 6	0 to 1 decrease
2030	0 to 6	0 to 1 decrease	0 to 6	0 to 1 decrease
2050	0 to 6	0 to 1 decrease	0 to 6	0 to 1 decrease

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 costs 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.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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 raw 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 to close to their source.
- Availability may change due to changes in the supplying industry.
- Efficiency is determined by the decarbonated fraction, which may vary significantly such as for recycled concrete fines.
- Further treatment steps may improve the utilisation, but need to be checked in terms of costs and environmental impacts.

4.13 Technology Paper No. 13: Fuel switch (coal/petcoke to oil/gas)

Fuel switching is one of the most discussed CO₂ reduction measures in the cement industry. It usually refers to the switch from coal to oil or gas. Due to its lower calorific value, the use of lignite leads to even higher relative CO₂ emissions than hard coal, but biomass is increasingly also coming into focus.

The fuels' variations on a global level in the different regions are significant. Gas and oil play a role in countries where these fuels are produced and local prices are comparatively low.

As the fuel-related CO₂ emissions are about one third of the total emissions (302 of 838 kg CO₂ per tonne of clinker), the CO₂ reduction potential is in principle significant if pure biomass use is assumed.

Pure biomass fuels used in the cement industry today are biomass wastes - mainly waste wood, rice 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 such as palm oil, corn, wood products or certain grass types (e.g. miscanthus or other fast-growing species). The use of biomass products as feedstock is related to questions on sustainability and greenhouse gas emissions from agriculture, forestry and land use. These materials have to be cropped, especially for later use as fuels. Today this is not relevant for the cement industry globally for economic reasons.

CO₂ legislation will have a significant impact on the quantities of biomass fuels which are available for the cement industry. Biomass costs are expected to increase and this will probably enable the separate planting of so-called cash crops to be used in different industry sectors. If, as 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. The biomass share of fuels is expected not to exceed 30% or 40% (corresponding to a maximum of 90 or 120 kg CO₂ 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.

Impact on energy consumption

thermal:	decrease of 200 increase of 100	MJ/t cli MJ/t cli	electric:	no significant change	kWh/t cli
----------	------------------------------------	----------------------	-----------	-----------------------------	-----------

CO₂ emission reduction

direct:	decrease/increase of 60 to 120	kg CO ₂ /t cli	indirect:	no significant change	kg CO ₂ /t cli
---------	-----------------------------------	---------------------------	-----------	-----------------------------	---------------------------

Material input

Hard coal Fuel oil or Natural gas	decrease of 121 kg/t cli increase of 75 kg/t cli increase of 90 Nm ³ /t cli
---	--

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Technical equipment of the plant
- Fuel costs
- Fuel type (C/H ratio, calorific value)
- CO₂ intensity of fuel mix
- Maximum possible substitution rate and sustainability in case of biomass fuel use

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	5 to 15	8 to 11 increase
2030	not applicable	not applicable	5 to 15	5 to 7 increase
2050	not applicable	not applicable	5 to 15	3 to 5 increase

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a
- Investment costs cover handling, storing, feeding and dosing facilities
- 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 CO₂ policies, availability on a regional level, etc.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Availability and price of biomass fuels will be the key factors
- Biomass fuels limit or reduce clinker capacity
- Many regions have a lack of experience with the use of biomass fuels in the clinker burning process

4.14 Technology Paper No. 14: Alternative fuels replacing conventional fossil fuels

The CO₂ emission reduction potential of alternative fuels is based on two effects: Firstly, many waste fuels contain certain biomass content. This content is calculated as CO₂ neutral. Secondly, most fossil waste fuels have lower CO₂ emission factors related to the calorific value than coal or petcoke. Pure biomass fuels used in the cement industry today are mainly wood waste, rice husks, 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 utilise up to 100% of waste or biomass fuels. Nevertheless, there are certain technical limitations, like the calorific value and the content of certain trace elements or chlorine. The calorific value of most organic material is comparatively low (10 to 18 GJ/t). For the kiln firing of the cement kiln typically an average calorific value of at least 20 to 22 GJ/t for the fuel mix is required. The firing of precalciners of modern cement kilns, in which up to 70% of the fuel input is realised, allows the use of low calorific fuels. Therefore, precalciner kilns are able to utilise at least 100% of low calorific (alternative and/or biomass) fuels in the calciner. 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. Although the use of these fuels lead to a higher energy demand it is possible that CO₂ emissions can be reduced.

The operation of cement kilns at very high substitution rates differs significantly from the operation with pure fossil fuels. The use of fuels with high concentrations of chlorine and sulphur in addition to the contribution of the raw materials may cause operational problems in the kiln system at very high substitution rates. This is attributed to the fact that circulating sulphur systems, together with chlorine and alkali circulating systems, may lead to increased coating formation in the kiln inlet, gas riser duct, the lower cyclone stages, and also formation of rings in the rotary kiln, subsequently leading to kiln stops. The 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 sulphur content in the kiln atmosphere. In conclusion, experience and tradition has shown, that alternative fuels can be used in the cement efficiently and that the technical operational experience as a major criterion has been developed across the sector.

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 consumption

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

CO₂ emission reduction

direct: decrease of 30 to 40 kg CO ₂ /t cli	indirect: increase of 1 to 2 kg CO ₂ /t cli
--	---

Material input

Alternative fuel mix (RDF, plastics, waste tyres, sewage sludge, etc.)	increase of 0.1 t/t cli
Fossil fuel (coal)	decrease of 0.07 t/t cli

Technical Readiness

TRL 2022: 9

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)
- CO₂ 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 cem]
2020	not applicable	not applicable	5 to 15	3 to 4 decrease
2030	not applicable	not applicable	5 to 15	3 to 4 decrease
2050	not applicable	not applicable	5 to 15	4 to 5 decrease

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a
- Investment costs cover handling, storing, feeding and dosing facilities
- Operational costs are expressed as savings and include only fuel cost savings as these are the main economic driver besides investment costs
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Availability, quality and price of waste fuels will be the key factors
 - Permitting conditions
 - Social acceptance of waste co-processing
 - Investment and operating costs of waste pre-processing facility
- Potentially negative impact on kiln operation to be controlled (lifetime of refractory materials, cyclone blockages, etc.)

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

For the use of alternative fuels, the fuel properties such as the ignition behaviour, the particle size, the calorific value or the moisture content must 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 approximately 13 GJ/t. For the main firing the fuel has to be fine enough (usually smaller than 20 mm) so that it burns completely in the gas phase, especially when feeding to the main burner. Alternatively, fuels can also be fed to the calciner or 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: < 2 GJ/t, pulp waste: 6 to 12 GJ/t, municipal solid wastes: 8 to 10 GJ/t, Refuse Derived Fuels (RDF): 16 - 23 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.

For the drying of RDF several applications have been installed in the cement industry in recent years (in most cases belt driers or flash dryers). For the drying of sewage sludge, drum dryers, screw dryers and belt dryers are used, although only a few applications are in operation so far. Hot waste air from the clinker cooler or raw gas from the preheater tower is used to deliver the required thermal energy. Cutting mills and chain mills are used for the comminution of RDF, but the technology is still emerging, particularly with regard to reducing excessive wear. The installation and operation of dryers and mills can increase the substitution rate of conventional fuels to alternative fuels. It requires CAPEX and OPEX that are amortised by fuel cost reduction compared to conventional fuels and the reduction of disturbances of the kiln operation.

A positive effect of the drying technology is that the moisture content of the fuels is reduced, so the kiln exhaust gas volume is reduced, resulting in a lower energy demand for the main ventilation fan and a lower thermal energy demand for the kiln system. In cases where the kiln fan operates at its full capacity, the installing of a fuel dryer can allow the kiln to operate at slightly higher capacity. This positive effect only counts when the moist waste gas from the drying process is not fed back into the kiln system for post-combustion purposes. In other cases, additional investments in additional filters, odour reduction systems 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 consumption

thermal:	increase of 0 to 50	MJ/t cli	electric:	decrease of 1 to increase of 3	kWh/t cli
----------	------------------------	----------	-----------	-----------------------------------	-----------

CO₂ emission reduction

direct:	decrease of 13 to 23	kg CO ₂ /t cli	indirect:	decrease of 0.6 to increase of 1.7	kg CO ₂ /t cli
---------	-------------------------	---------------------------	-----------	---------------------------------------	---------------------------

Material input

Alternative fuel: Coarse RDF or Alternative fuel: Wet RDF or Alternative fuel: Sewage sludge, 80% water content	grinding of 0.02	t/t cli
	pre-drying of 0.04	t/t cli
	pre-drying of 0.16	t/t cli

Technical Readiness

TRL 2022: grinding: 8 pre-drying: 9

The main influencing parameters are

- 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]
2020	2 to 20	decrease of up to 2.2	2 to 20	decrease of up to 2.2
2030	2 to 20	decrease of up to 2.1	2 to 20	decrease of up to 2.1
2050	2 to 20	decrease of up to 2.1	2 to 20	decrease of up to 2.1

Remarks:

- CAPEX includes dryer or mill, exhaust fan and exhaust pipes. Depending on the fuel type and the alternative fuel increase rate, additional equipment can be necessary (i.e. exhaust gas filters and odour reduction system, circulation thermal oil system, increased storage and dosing capacity for the fuels)
- Operational costs depend on the fuel feedstock and related cost structures. Due to the use of wet materials it is assumed that those materials can be purchased at zero costs.
- 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 substitution by alternative fuels and reflects the increased electrical power use. The CO₂ reduction potential is related to an increased fuel substitution by 10 to 20 %
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.16 Technology Paper No. 16: Pre-combustion chambers and gasification

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) limits the feasible alternative fuel substitution rate because of causing instability of the process. 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, H₂ and CH₄ and therefore offers a certain heating value.

Standard 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 (~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) and stabilise the kiln operation when using e.g. coarse or inhomogeneous materials. Stepped combustion on grates is also used to properly combust even different coarse waste materials. The mineral fraction and ashes of the waste fuels become part of the product. These advanced solutions are commercially available, but rarely applied. Even though the maintenance effort is higher, these systems can be more cost-efficient compared to the pre-treatment of waste materials.

Using gasification processes, a lean gas could be provided to the calciner or kiln inlet area, where it is completely oxidised. In this way the energy input could be homogenised 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 could counteract the negative 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 be either disposed of 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 the clogging of lean gas tubes to the calciner, which again places requirements on the fuel quality. In certain applications the introduction of lean gas could 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 fluidised bed reactor. Such systems are commercially available but still not widespread.

Research projects are also focussing 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/m³ using air as media, and up to 14 MJ/m³ using steam. The application of plasma gasification in the cement industry has been investigated but has not been further developed for larger scale use due to the low economic viability.

Impact on energy consumption

thermal:	increase of up to 150	MJ/t cli	electric:	increase of 0 to 5	kWh/t cli
----------	-----------------------	----------	-----------	--------------------	-----------

CO₂ emission reduction

direct:	decrease of up to 25	kg CO ₂ /t cli	indirect:	increase of up to 3	kg CO ₂ /t cli
---------	----------------------	---------------------------	-----------	---------------------	---------------------------

Material input

alternative fuels, 50% biomass 0.5 mm <size< 50 mm (100 mm), metals >6 mm, LCV <10 MJ/kg	0.05 to 0.08	t/t cli
--	--------------	---------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Type of available materials and substitution rate
 - CO₂ reduction potential mainly depends on the substitution rate of alternative fuels and their biogenic fraction
- Used technology: In the case of plasma gasification higher thermal reduction is expected at higher electrical demand, and the CO₂ footprint of the power mix

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	8 to 12	decrease of up to 1.9	8 to 12	decrease of up to 1.9
2030	8 to 12	decrease of up to 1.9	8 to 12	decrease of up to 1.9
2050	8 to 12	decrease of up to 1.9	8 to 12	decrease of up to 1.9

Remarks:

- The cost estimation is based on a designed clinker capacity of 2 Mio. t/a. Additional costs for fuel storage and transport as well as demolishing old equipment 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 10 to 20% through the use of a typical pre-combustion chamber. Due to the use of coarse and wet material it is assumed that those materials can be purchased at zero costs. The costs estimation does not include losses of revenue during kiln stops caused by the direct use of alternative fuels.

- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Gasification and pre-combustion chambers are an option for the combustion of difficult combustible and coarse fuels and aim at the stabilisation of the clinker burning process. The costs for pre-treatment of these types of fuels are avoided, which can in certain cases be higher
- Prices for alternative fuels are expected to rise at steeper rates than fossil fuels, which strongly influences the forecast of operational costs in 2030 and 2050
- Suitable for locations where the availability of appropriate fuels is limited

4.17 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 to 2.8 MPa and 180 to 210°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 and wet fractions of municipal solid waste. After a few hours the HTC Hydrochar 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 24 kWh electrical energy and 180 kWh of thermal energy (650 MJ) per ton of input sewage sludge is required to maintain the HTC process incl. the final drying step. 1 ton of sewage sludge with a dry matter content of 25% results in 210 kg of Hydrochar with 10% moisture. Thus, the specific energy demand for the production of 1 ton of Hydrochar is 115 kWh electricity and 3,100 MJ process heat. The produced char is hydrophobic. Mechanical dewatering down to 35% 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. As of 2022, first industrial projects have been started or are already in continuous operation in China, Finland, Sweden, Spain, the UK, Mexico, France, Belgium, Japan and the USA. Specific total costs (CAPEX+OPEX) range between 200 € and 300 € per ton of Hydrochar, depending on the energy cost and the project size. 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. Phosphorus recovery is available in pilot scale from different technology providers in 2022, reporting recovery rates between 60 and 90%. A potential increase of the sulphate content during Phosphorus recovery might limit the share of Hydrochar in the fuel mix for 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. The standardisation of torrefied fuel products is ongoing. They may allow the increase of biomass use in industrial plants at the expense of about 14 kg indirect CO₂/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. Questions on sustainability of the biomass feedstock, land use and indirect CO₂ release are being discussed for large-scale use and production of primary biomass for torrefaction.

Impact on energy consumption

thermal: increase of 168 MJ/t cli	electric: increase of 7 kWh/t cli
-----------------------------------	-----------------------------------

CO₂ emission reduction

direct: decrease of 60 kg CO ₂ /t cli	indirect: increase of 3.9 to 9.4 kg CO ₂ /t cli
--	--

Material input

biomass wastes, e.g. sewage sludge	increase of 0.17 to 0.27 t/t cli
fossil fuel demand, e.g. lignite	decrease of 0.03 t/t cli

Technical Readiness

TRL 2022: TRL 7 to 9, applicability for industry at TRL >8 expected around: now and 2025

The main influencing parameters are

- Availability of sustainable biomass feedstock
- Increase of the biomass content of fuel mix in the cement plant, here assumed 20% increase and substitution rate
- Residual moisture of Hydrochar and resulting lower heating value
- Energy demand of additional 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]
2020	not available	not available	included in operational cost	increase of 4.5 to 7.8
2030	not available	not available	included in operational cost	increase of 3.0 to 5.4
2050	not available	not available	included in operational cost	increase of 1.9 to 3.7

Remarks:

- CAPEX: investment is transformed to a gate fee (OPEX)
- OPEX: The cost estimation is performed for the inclusion of the HTC process at an existing cement plant (retrofit) by transforming indicated gate fees for an untreated biomass feedstock and for complete cost coverage to operational costs per ton of cement. The total additional costs indicated in the table would apply in case of no gate fee
- Extraction and recovery of phosphorus is estimated to add 50% to indicated total additional costs. The increased costs could be covered or even exceeded by significantly higher expected gate fees in the case of phosphorus recovery
- The cost per CO₂ avoidance highly depends on the gate fee. In a case with no gate fee the total additional cost of a HTC plant yields an estimated very high specific CO₂

abatement cost of more than 100 €/t CO₂ avoided (4.5 to 7.8 €/t cem for a net decrease of 44 kg CO₂/t cem)

- Fuel products from the torrefaction of solid biomass show a very similar estimated impact on operational costs
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling factors

- Sewage sludge as a biogenic waste feedstock results in HTC char with low net calorific values of about 12 to 16 MJ/kg creating limited potential for fossil fuel substitution at the kiln main burner and high energy-specific costs
- The 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 (LULUCF)
- A global market for sewage sludge up to 170 Mt/a amounts to around 40 Mt/a HTC char as a theoretic maximum
- Further restrictions on the agricultural usage of sewage sludge in many countries lead to an increased demand for its treatment and use
- A decentralized installation of HTC plants at the waste water treatment plants allows for considerably less effort for transportation due to the reduction of volume by factor of 4

4.18 Technology Paper No. 18: Use of hydrogen as fuel

The use of hydrogen gas in addition to alternative fuels (AF) has a vast potential for reducing fuel-related CO₂-emissions in the cement industry. When combusted, pure hydrogen emits only water (H₂O), thus no CO₂. Another benefit of using hydrogen in the cement industry is the high efficiency compared to other industries, since no process-related compression of the gas is needed. The biggest challenge is the availability of sufficient carbon neutral power, which is needed to produce H₂. At present, the use of hydrogen is negligible in the cement industry. In 2022 the largest known kiln test was performed within the *Fuel Switch* project (BEIS, Mineral Products Association) in the UK, where a kiln was operated with a net-carbon-zero fuel mix at the primary burner. The observations and results from this project are the most important basis for this technology paper. The fuel mix used included a hydrogen share of ca. 40% of the thermal energy used in the kiln primary burner. The result of this short-term test of a few hours was that the technical implementation of H₂ use in the kiln firing is possible.

Even taking the short test period into account, the effects of hydrogen on the burning process have been smaller than expected. According to pre-studies, it had been expected that hydrogen would draw the flame closer to the burner tip and increase the temperature of the core flame due to its better ignition properties and its higher calorific value. Furthermore, a H₂ flame has significantly less radiation compared to a solid fuel flame, which should decrease the heat transfer to the clinker bed. Both the shift of the flame position and its temperature increase were successfully avoided by increasing the H₂ injection velocity. The total thermal energy consumption seems to be unaffected, whilst the oxygen demand decreases with increasing the hydrogen substitution rate. Compared to coal, hydrogen needs less air to combust, which leads to a higher oxygen level at the kiln inlet. If combusted with air, the temperature must be controlled, just as in any natural gas- or coal-fired kiln, in order to prohibit thermal formation of nitrous oxides. Impacts on clinker quality were not visible under these conditions, but this statement also has to be seen against the background of the short test period. The missing ash from replaced fuels has to be compensated in the kiln feed mix.

In the future scenario of 2050, where an average share of 10% H₂ of the total thermal energy demand has been assumed, the fuel-based CO₂ emissions decrease by ca. 10% respectively. Long-term tests need to be carried out in order to study the influence of hydrogen on the clinker burning process, and long-term equipment corrosion over a longer period of time.

H₂ can be supplied externally in small quantities to a cement plant by truck or train, if larger volumes are needed a pipeline or electrolysis on site is required. In this assessment, hydrogen is produced by water electrolysis. The electrolysis consumes 44 MWh electric energy to produce 1 ton of H₂ with an electrolyser efficiency of 75%. Its production and use are assessed as carbon neutral i.e. the used power originates completely from carbon neutral sources. The mass-based calorific value of hydrogen is higher than that of oil or coke (120 MJ/kg) but, on the other hand, the volume-based calorific value is very low (10.8 MJ/m³). As H₂ is transported in gaseous or liquid form, very high pressure (500 – 1000 bar) has to be applied in order to allow the transport H₂ in trucks or railway wagons. The injection of H₂ into the cement kiln burner is done close to atmospheric pressure level, meaning that the cement plant needs to install pressure reducing valves. If H₂ is produced on-site by water electrolysis, depressurization is needed only to a small extent, this reduces the power consumption overall.

Currently, the usage of hydrogen is not considered in most cement plants as a viable option due to lack of access and/or affordability, but prices for hydrogen are expected to settle at 1.5 €/kg (12.5 €/GJ) in 2050. If green hydrogen is produced locally at the plant via an electrolyser, it would contribute to the indirect electrification of the clinker production process by providing thermal energy through electricity. The performance of electrolysers is expected to increase in the future. With new capillary electrolysis technologies being developed, efficiencies of 95% are possible. Implementing a local hydrogen electrolyser also has other benefits for the plant: The produced O₂ can be used to enrich the flame for an increased clinker production or improve the combustion of alternative fuels in the main burner.

Impact on energy consumption

thermal:	not affected	MJ/t cli	electric:	not affected	kWh/t cli
----------	--------------	----------	-----------	--------------	-----------

CO₂ emission reduction

direct:	decrease of 30	kg CO ₂ /t cli	indirect:	not affected	kg CO ₂ /t cli
---------	----------------	---------------------------	-----------	--------------	---------------------------

Material input

Hydrogen	0.0028	t/t cli
----------	--------	---------

Technical Readiness

TRL 2022: 6

applicability for industry at TRL >8 expected around: 2040

The main influencing parameters are

- Cost of hydrogen
- Hydrogen injection velocity, rate and location
- Availability of hydrogen (substitution rate, size of buffer tank, piping)
- Flame shape and heat radiation
- If locally produced via electrolyser: co-benefit in using the O₂ which is additionally produced

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	2.3 to 4.5	5.4 increase
2030	not applicable	not applicable	2.3 to 4.5	3.4 increase
2050	not applicable	not applicable	2.3 to 4.5	1.9 increase

Remarks:

- Cost estimation is based on a substitution rate of 10% hydrogen in a 6000 t_{cli}/d plant
- H₂ supply and consumption are considered in OPEX; No CAPEX for electrolysers is included
- Assumed hydrogen prices: 3.2 €/kg (2020), 2.2 €/kg (2030), 1.5 €/kg (2050)

- Prices for an injection lance, pressure reducing skids and piping are accumulated with a scale-up
- Size for buffer tanks is designed to store 1 h worth of hydrogen supply at a feed rate of 0.7 t H₂ / h with a storage pressure of 40 bar (usable until 5 bar)
- Hydrogen-related electricity consumption is compensated by the decline of fossil fuel usage
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Usage of hydrogen in kiln and calciner burner needs to be studied long-term
- Availability of sufficient carbon neutral H₂
- Global availability of piping, burner injectors and storage tanks for 2050 undefined
- Safety regulations, trained personnel, hydrogen leakage prevention
- If self-produced H₂: High voltage power grid connection

4.19 Technology Paper No. 19: Electrification, plasma and other technologies

Currently there are only a few projects within the cement industry, which are focusing on the electrification of the cement manufacturing process. In general, the heat transfer through electrification appears promising for the cement industry and can be accomplished by different methods, such as plasma technology, induction heating, resistive electrical heating and microwave heating. However, none of these concepts has been applied industrially in cement manufacturing yet and only a few conceptual applications and methods have been reported. As electrical processes would replace fuel combustion, approximately 35% of total the CO₂ emission could be abated.

The noteworthy LEILAC project features an alternative calciner design, which allows indirect heat transfer either through the burning of fuels or through electrical energy (see also Technology Paper No. 48).

Plasma burner

Plasma heating is based on the generation of a hot beam of ionized plasma, which is generated by the input of electrical energy in gas, often triggered by an arc discharge (or high frequency field). Plasma heating uses flowing gas (O₂, N₂, CO, air, steam etc.). As a result, heat transfer to the product is mainly achieved by convection and can be influenced by manipulating gas type and flow. The plasma arc can produce a wide spectrum of temperatures ranging from 1500°C to over 7000°C. Plasma torches have been built up to a capacity of a few MW_{th}.

Within the CemZero project, initiated by Vattenfall and Cementa in 2017, a pre-feasibility study evaluated the electrification of the cement production process by applying plasma technologies for the heat transfer in a cement kiln. Several scenarios for the full electrification were simulated and examined on laboratory scale. Based on these results it was concluded to further investigate the thermal electrification of cement manufacturing on a higher scale. In a project of the British Mineral Products Association (MPA), a simulation study and a physical short-term test (30 minutes) at an industrial cement kiln was conducted in order to evaluate the use of a plasma burner in the calciner. It was demonstrated that the plasma burner was able to withstand the harsh environment in the calciner and could deliver heat to the process. The heat produced by the plasma burner was about 70 kW. Due to the short operation period and the small amount of thermal energy originating from the plasma torch, no final conclusion could be drawn for the evaluation of the electrified thermal input.

Induction heating

Induction heating is also based on the generation of Joule heat. Usually, the electrical current is directly induced into the material to be heated, assuming the material is electro-conductive. Otherwise, the current is induced into a container, which contains a fluid, which in turn can be used to heat the material.

However, it is not yet known, which technology will be used for the heat generation through electricity. It is important to note, that the meal has a low electrical conductivity and is non-magnetic, so that the thermal energy has to be transferred indirectly through heat exchange from a conductive and magnetic material.

Microwave heating

The heat is transmitted through electromagnetic radiation in the microwave range into the material. Principally, the meal can be heated up without direct contact with the power source. On the other hand, cement raw material has poor microwave absorbing capacity. Quartz in particular is transparent to microwaves at low temperatures. Therefore, microwave heating of cement raw meal is very inefficient, also due to the reflection of the microwaves back into the magnetrons.

Resistive electrical heating

In resistive electrical heating thermal energy is generated by a current in a resistive element. The generated heat can then be transferred to the meal or process gas in different ways, either directly through the convection of the gas or indirectly through conduction and radiation. As the availability of materials, which can withstand the required high temperatures in an oxidizing atmosphere in combination with a dusty environment is rather limited, this technology seems does not seem to be promising for the clinker burning process.

Impact on energy consumption

thermal:	decrease of up to 3352	MJ/t cli	electric:	increase of 1000 to 3200	kWh/t cli
----------	------------------------	----------	-----------	--------------------------	-----------

CO₂ emission reduction

direct:	decrease 296	kg CO ₂ /t cli	indirect:	increase 600 to 1800	kg CO ₂ /t cli
---------	--------------	---------------------------	-----------	----------------------	---------------------------

Material input

plasma gas	not available	t/t cli
------------	---------------	---------

Technical Readiness

Technology Readiness Level

TRL 2022: 4 applicability for industry at TRL > 8 expected about: 2030-2040

The main influencing parameters are

- availability of carbon neutral electricity
- infrastructure for electrical power supply
- efficiency for energy transfer from electrical power to heat
- final process design for electrified cement plants
- reliability of new electrical thermal components

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not available	57 to 205 increase	not available	not available
2030	not available	62 to 221 increase	not available	not available
2050	not available	49 to 180 increase	not available	not available

Remarks:

- The estimation of operational costs is based on the substitution of thermal energy from fuel by electrified heat transfer through a plasma torch with efficiencies between 25 and 75%
- The costs for the plasma gas are not included
- Operational costs are expressed as additional costs compared to a conventional kiln
- Plasma torches with the required capacity are not available today. It is assumed that a first-of-a-kind-plant might have significant changes in process technology, therefore no investment cost estimation can be made. Investment costs are not available for high power plasma torch systems
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Choice for process design
- Availability of carbon neutral electrical energy
- Future development of plasma technology to larger capacities

4.20 Technology Paper No. 20: Recycled concrete fines as raw material for clinker production

The proportion of alternative raw materials in the production of Portland cement clinker is usually comparatively low (often less than 2%). This is due to the fact that the raw material composition for clinker production predominantly requires calcium-containing minerals, which can currently only be covered to a small extent by alternative raw materials. In alternative raw materials currently being used, calcium is mostly bound as carbonate, so that CO₂ is released accordingly during burning. Therefore, alternative raw materials which provide a carbonate-free source of calcium are particularly interesting.

During its service life, hardened cement paste re-integrates CO₂ to an amount which corresponds – at a conservative estimate - to approx. 20% of the CO₂ released from the limestone during clinker production in a natural and slow way. Approx. 80% of the hardened cement paste in concrete elements remains uncarbonated and represents a potential CO₂-free source of calcium for clinker production.

The technologies currently used for crushing and processing concrete do not yet provide a selective separation of the cement paste. With current processing methods, around 70 mass-% recycled aggregate (ca. 80% aggregate, 20% cement paste) and 30 mass-% recycled concrete fines (≤ 2 mm) are recovered from crushed concrete. The resulting recycled aggregates can be directly reused for the production of fresh concrete instead of natural gravel and sand. Ground recycled concrete fines are particularly suitable for use as raw meal component for clinker production and as a cement component (see Technology Paper 40). Recycled concrete fines, obtained by usual crushing and processing of crushed concrete, contain approx. 25 to 30 mass-% hardened cement and approx. 70 to 75 mass-% of fine aggregate. Currently, various processing methods for selective separating of fine hardened cement paste and aggregate from waste concrete are being tested in the industry (e.g. electrodynamic fragmentation in combination with various crusher stages). In trials with optimised selective processes, the proportion of hardened cement paste could increase to approx. 60 mass-%. Furthermore, the composition of concrete fines corresponds to that of the fine components of the concrete. Depending on the exposure of the concrete, they may also contain chloride or sulphates, among other things, which must be taken into account when using them as an alternative material for clinker production. In a finely ground state and stored under appropriate alternating humidity conditions, the CO₂ uptake of hardened cement paste increases. In the case of stockpile storage of separated hardened cement paste, only the outer centimetres of the stockpile usually carbonate, so that the amount of CO₂-free calcium of the material should remain over a longer period of time.

In this respect, the hardened cement paste in recycled concrete fines represents a large, mostly carbonate-free source of calcium that can be used again for the clinker production. Current available concrete fines contain mainly sand (silicon dioxide) in addition to uncarbonated calcium silicate hydrate (CSH) phases and portlandite (Ca(OH)₂). The content of sand mostly limits the use of concrete fines as an alternative raw meal component, since the high silicon content must be balanced out by adding limestone in such a way that the desired clinker phases can be produced. Assuming an average limestone quality in a cement plant and an average recycled concrete fines composition, up to around 10 mass-% of the raw material mixture can be substituted from a technical point of view. Higher quantities are possible, the purer the hardened cement paste can be recovered during crushing (reduction of the sand content) and the purer the available limestone is.

Therefore, it is important to further develop the processing methods in order to achieve the highest possible sand separation. The CO₂ savings potential of the recycled concrete fines depends on their content of Portland cement clinker and other calcium-containing cement constituents. Limestone constituents in cement(paste) or limestone aggregates in concrete reduce this potential.

Currently, crushed concrete from constructions is hardly used for the production of cement and concrete. Instead, almost all of the processed crushed concrete quantities are used for road sub-construction or are mixed with soil material to improve its properties such as for frost protection layers. Compared to the existing recycling practice of concrete, new source streams must be initiated which take into account the complete reuse of materials used in crushed concrete for the production of new fresh concrete (recycled aggregate) as well as for clinker and cement production (recycled cement paste). Furthermore, a corresponding infrastructure for crushed concrete processing, an adequate quality assurance and a transport system for the respective source streams must be established. The large quantities of material to be handled are certainly a challenge. For one tonne of (pure) hardened cement paste, theoretically around 5 t of waste concrete have to be processed. The separation of waste concrete during demolition and the separation of the hardened cement paste from the aggregate must be improved.

The technical potential of these materials is the subject of current research.

The estimations below are based on a 10 mass-% substitution of raw material mixture by recycled concrete fines. Further assumptions:

- Proportion of cement paste in recycled concrete fines (50 mass-%)
- Proportion of cement (Portland cement with 95 mass-% clinker) in cement paste (w/c = 50%)
- 20% of process CO₂ of clinker via natural carbonation during service life

Impact on energy consumption

thermal:	decrease of 201	MJ/t cli	electric:	no significant change	kWh/t cli
----------	-----------------	----------	-----------	-----------------------	-----------

CO₂ emission reduction

direct:	decrease of 68	kg CO ₂ /t cli	indirect:	no significant change	kg CO ₂ /t cli
---------	----------------	---------------------------	-----------	-----------------------	---------------------------

Material input

raw material	decrease of 0.16	t/t cli
recycled concrete fines	increase of 0.16	t/t cli

Technical Readiness

TRL 2022: 8, for selective separation technique producing fines with 50% cement paste applicability for industry at TRL > 8 expected about: 2025

The main influencing parameters are

- High silicon content of recycled concrete fines reduces substitution rate
- High substitution requires high limestone quality in raw meal
- Grindability as typical raw meal
- CO₂ content of recycled concrete fines

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	not available	0.8 to 0.2 decrease
2030	not applicable	not applicable	not available	0.8 decrease
2050	not applicable	not applicable	not available	0.8 decrease

Remarks:

- All technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Currently, crushed concrete from constructions is hardly used for the production of cement and concrete; it is mainly used for road substructures
- Processing (separation, crushing, fractionation, etc.) of crushed concrete must be improved in order to obtain recycled concrete fines
- Long transport distances from demolition site to cement production
- Corresponding infrastructure for processing of waste concrete, an adequate quality assurance and transport systems must be established

4.21 Technology Paper No. 21: Advanced plant control and AI-supported control systems

The stability of the continuous production process in cement plants has a big influence on its energy efficiency. Due to varying material or fuel properties, the clinker burning process and the grinding processes are constantly changing. Non-automated processes or non-optimised process control systems may lead to capacity decrease, heat losses and moreover to unstable process conditions including more operational stops. This can cause increased electrical and fuel demand, e.g. at the kiln for reheating the sintering zone. Advanced plant control systems, often called 'expert systems', are significant measures to optimise the comminution and combustion processes. Based on a combination of different approaches like predictive process models, fuzzy control or artificial intelligence (AI) and machine learning (ML), process conditions are constantly supervised whilst underlying PID setpoints are optimised with respect to the many interdependencies between the process parameters. With the ongoing digitalisation of cement production, the availability and quality of data has been increased, paving the way for trustworthy and performant AI-supported control and optimisation tools.

At the kiln both raw materials and the fuel mix can be improved through the 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. 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 and more even product quality under process-controlled mill operation have also been reported. Typical parameters controlled in such systems are separator speed, fresh feed rate or air flow. Quality parameters can either be measured or determined by the use of soft-sensors (software sensors based on ML) and then directly linked to process parameters. Thus, safety margins such as for temperature or fineness can be reduced.

Thermal and electrical energy savings relating to the use of control systems compared to a cement plant without such a system may vary typically between 50 to 200 MJ/t cli and 0 to 2.5 kWh/t cem. More consistent clinker and cement quality can also support the further reduction of the clinker factor. Often, a payback period of 2 years is typical for control systems. Successful application of advanced control systems requires a mechanically stable process. Savings from previous optimisation measures e.g. material distribution are not considered here. The possible reduction of thermal and electrical energy consumption strongly depends on the technical equipment and its availability, the initial level of plant automation, the instrumentation, data availability and data quality as well as the qualification and acceptance among the operating staff.

Impact on energy consumption

thermal:	decrease of 20 to 170	MJ/t cli	electric:	decrease of 1.5 to 3.2	kWh/t cem
----------	--------------------------	----------	-----------	---------------------------	-----------

CO₂ emission reduction

direct:	decrease of 1 to 11	kg CO ₂ /t cem	indirect:	decrease of 0.9 to 1.8	kg CO ₂ /t cem
---------	------------------------	---------------------------	-----------	---------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 8-9

The main influencing parameters are

- Technical plant equipment and mechanical condition
- Initial status of plant automation
- Instrumentation
- Data infrastructure and data quality
- Education of staff and acceptance
- CO₂ intensity of fuels

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	0.25 to 5.0	0.2 to 0.8 decrease	0.25 to 5.0	0.2 to 0.8 decrease
2030	0.25 to 5.0	0.2 to 0.8 decrease	0.25 to 5.0	0.2 to 0.8 decrease
2050	0.25 to 5.0	0.2 to 0.8 decrease	0.25 to 5.0	0.2 to 0.8 decrease

Remarks:

- Investment figures may vary significantly due to plant configuration and the level of instrumentation and automation.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Existing plant constellation predetermines further needs of equipment
- Processes need to be mechanically stable before application of new control systems – “good housekeeping” is required
- Processes should be optimised before installing new control systems
- Educational level of operators and staff is of importance for process controlling
- Fostering of acceptance for new modes of operation and new control technology is crucial for successful application
- Expert control systems simulate the best operator by using information from various stages in the process – but they strongly depend on the quality of these sources of information

4.22 Technology Paper No. 22: Variable speed drives for fans

Electrical drives for mills, the kiln and for fans are the main power consumers in the cement production process. Most of the other motors are relatively small-sized and fixed-speed models. Kiln drives are in general equipped with variable speed drives (VSDs) for process reasons, and VRMs or HPGRs use VSDs in some cases to increase process stability. The electrical energy consumption of fans can be reduced significantly because of oversized equipment and large variations of the dust load. Other motors, e.g. of transport or ball mills, can often not be operated in partial load for process-related reasons. In the past, dampers and bypass-control systems were used to reduce the air flow, but most of the plants are already retrofitted with VSDs at the relevant fans (e.g. ID fan, clinker cooler fans, kiln exhaust fan, mill ventilation). There is still potential for further improvement.

Therefore, the control method employed has a major effect on the operating costs. Frequency controlled equipment is used in most cement plants, but the application may vary widely depending on electricity costs. In particular, big fans (e.g. ID fan, cooler fan, kiln exhaust fan) are often equipped with variable speed drives.

Variable speed drives can help to reduce power use in cement plants. Assuming a low degree of implementation, power savings of theoretically up to 3.4 kWh/t cem are achievable. This value is based on a calculation which includes the replacement of the largest fans (ID fans, clinker cooler fans and mill separator fans) and therefore do not apply to new installations or already retrofitted cement plants.

The use of VSDs has a major effect on the operating costs through energy savings. The power consumption of fans changes with the third power to the speed of the unit. This means that the reduction of the rotational speed by 10% leads to energy savings of almost 25%. The electrical energy savings through frequency-controlled drives may therefore vary in a wide range (in practice between 7 to 60% related to the drive itself). Additional benefits of variable speed drives are the process controllability via a process control system, reduced maintenance costs, reduced motor noise, and the elimination of fan vibration. On the other hand, energy savings may be limited if the devices are operated close to maximum capacity. Energy savings can also be achieved by the replacement of old, inefficient motors (as described in Technology Paper 23).

Impact on energy consumption

thermal:	not applicable	electric:	decrease of 0 to 3.4	kWh/t cem
----------	----------------	-----------	----------------------	-----------

CO2 emission reduction

direct:	not applicable	indirect:	decrease of 0 to 1.9	kg CO ₂ /t cem
---------	----------------	-----------	----------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Number of variable speed drives installed at the fans (a complete update of ID fan, cooler and mill fans from throttle control to VSD can result in the before-mentioned reduction of 3.4 kWh/t cem)
- Increase of differential pressure by use of throttles (e.g. flaps or sliders) in operation
- Power consumption
- Application area
- CO₂ intensity of (external) power supply

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	0.13 to 0.19 (1.000 kW)	0 to 0.32 decrease
2030	not applicable	not applicable	0.13 to 0.19 (1.000 kW)	0 to 0.34 decrease
2050	not applicable	not applicable	0.13 to 0.19 (1.000 kW)	0 to 0.28 decrease

Remarks:

- The above-mentioned investment cost refers at its maximum to the installation of frequency converters and new motors at the cement mill separator fans, the clinker cooler fans and the ID fan. Additional installation costs of 30% are considered in the investment costs. The operational cost strongly depends on the possible speed reduction of the fan, due to replacement of mechanical air flow control units (e.g. throttles). A fan speed reduction of 10% at the kiln site and 10 to 20% at the mill separator fans (5% and 80% time slice) were assumed. Depreciation, interest and inflation are not included in operational costs.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Process control system with frequency controlled drives may stabilise process conditions
- Future developments can decrease investment and operational costs further on
- Economics depend on:
 - CO₂ and power price
 - Number of replaced throttles and resulting reduction of differential pressure

4.23 Technology Paper No. 23: 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 dissipated in motors and as waste heat. The generation of compressed air can represent more than 50% of the electrical energy consumed by cross-sectional technologies in a cement plant, which include compressed air, lighting, and the 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 centralised 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% in energy demand. The elimination of leakages, the 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.

Depending on its size and its process technology, a cement plant can have from 350 up to more than 1000 motors to operate conveyors, pumps, small fans and blowers. The replacement of standard efficiency (IE1) by premium and super premium efficiency motors (Class IE3 and IE4 respectively) can represent up to 12% nominal efficiency gains, depending on the size of the motor. Motors with higher installed power have however lower potential efficiency gains (up to 3%). The substitution of motors is usually done in a stepwise fashion, also taking into account spare motors stored in the plant. Therefore, a policy of purchasing only premium and super premium efficiency motors 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/IE4 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 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 consumption

thermal:	not applicable	MJ/t cem	electric:	decrease of 3 to 5.5	kWh/t cem
----------	----------------	----------	-----------	-------------------------	-----------

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cem	indirect:	decrease of 2 to 3	kg CO ₂ /t cem
---------	----------------	---------------------------	-----------	-----------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Initial efficiency level of installed 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]
2020	depends on measure/ technology	depends on measure/ technology	depends on measure/ technology	0.3 to 0.5 decrease
2030	depends on measure/ technology	depends on measure/ technology	depends on measure/ technology	0.33 to 0.55 decrease
2050	depends on measure/ technology	depends on measure/ technology	depends on measure/ technology	0.27 to 0.45 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 condition 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.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.24 Technology Paper No. 24: 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 to establish objectives, targets and action plans to reduce energy use in accordance with the organisation's energy policy. The energy management system sets a focus on continuous monitoring and the potential for the improvement of energy use, its management, and 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 regarding 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. 23). 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 opportunities for improvement (i.e. demand side management - see Technology Paper No. 25) 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, the identification of influencing parameters and the monitoring of normalised energy performance indicators. Management audits are a further 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 units of the plant (significant energy users, so called SEU's) and all relevant energy performance indicators:

- Evaluation of the energy demand (fuel and electricity) of all relevant departments (e.g. raw material quarrying and preparation, clinker burning and cooling, cement and fuel grinding, as well as auxiliaries based on information provided by the operator
- Evaluation of plant design with regard to energy aspects
- Evaluation of energy objectives and action plans
- Assessment of these characteristics in comparison with state-of-the-art cement production

Experience shows that energy management systems are an effective tool to continuously achieve further improvements in saving thermal and electrical energy.

Impact on energy consumption

thermal:	not applicable	MJ/t cem	electric:	not applicable	kWh/t cem
----------	----------------	----------	-----------	----------------	-----------

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cem	indirect:	not applicable	kg CO ₂ /t cem
---------	----------------	---------------------------	-----------	----------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Energy policy of the company
- Energy prices
- Improvement management plan

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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, enabling framework

- 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
- Incentives through legal regulation i.e. reduction of energy taxes or fees

4.25 Technology Paper No. 25: 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, aiming at decarbonising the power sector. Wind and solar energy resources depend on current local weather conditions. This makes their availability subject to fluctuations and adds a degree of unpredictability in terms of the management of the energy supply. During strong wind periods it may occur that not the entire electrical energy from wind power generation can be fed into the transmission grid and a certain share remains unused. The reason for such energy losses is a temporal mismatch between supply and demand and the limited electrical transmission capacity of power grids. Current storage capacities for electrical energy are often limited in capacity, very costly and related to efficiency losses. Thus, a growing share of renewables in electrical power production demands more flexible energy management strategies and the inclusion of demand side management applications of suitable industry processes which can react to fast changing availability of electrical power.

In general, 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, for example at night (e.g. 8 of 24 h), when the electrical energy demand and consequently the prices are reduced. However, with an increasing energy supply from renewable energy sources, the periods of maximum available electrical energy and the corresponding volatility of energy prices may change significantly. Nowadays many cement plants have dedicated schedules and procedures for planning their 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 renewable energy sources, additional management strategies and options for flexible production processes are envisaged.

From the perspective of the cement plant's demand side, a flexible grinding approach for raw meal and cement production is possible to stabilise the electrical transmission system through the operation time shifting of electrical power intensive processes. The management of silo and production capacities could then be executed similarly to a battery operation for more efficient utilisation of excess renewable energy. However, there are certain constraints regarding the application in different grinding processes. Sufficient silo capacities and the respective mill utilisation are especially relevant. Raw mills usually have a high utilisation factor to ensure continuous kiln operation and are therefore less suitable for demand side management in general. Furthermore, the handling and utilisation of exhaust gas from the kiln to pre-dry raw material in the raw mill has to be considered.

On the other hand, an important advantage is a decrease in electrical energy demand during periods with insufficient power generation from renewable sources, thus avoiding fossil fuel use in the power sector. In best case scenarios the mills are subsequently able to grind at full capacity during times of abundant renewable energy. This would enable the fast compensation of emerging production deficits through shifted mill operation time slots. On the other hand, drawbacks can arise from inefficient mill operation with an increased number of stop-pages and increasing wear progress and maintenance effort for cement mills and auxiliary equipment. Moreover, potential negative impacts on product quality during the mill start-up and shut-down periods have to be considered.

The minimising on-off operation and assuring minimum mill operating time periods must therefore be part of an integrated management strategy for the efficient, flexible use of renewable energy for cement production.

Summarised, the installed mill power, the mill utilisation factor and the local available silo capacities determine the potential of a cement plant for using renewable power. From an economic point of view, the future development of electrical power prices and the volatility of these determine the achievable revenue potential for cement producers.

Currently, projects directly supplying renewable power to cement plants or in a construction phase have been reported worldwide, e.g. in Bulgaria, Egypt, Germany, India, Morocco, Mexico and Spain. Some cement producers have invested in wind farms or solar plants or signed contracts with renewable energy producers in order to directly use renewable energy for cement production, and in this way already contribute to the reduction of indirect CO₂ emissions.

Impact on energy consumption

thermal:	not applicable	electric:	not available, increase possible
----------	----------------	-----------	-------------------------------------

CO₂ emission reduction

direct:	not applicable	indirect:	decrease of 1 to 8	kg CO ₂ /t cem
---------	----------------	-----------	-----------------------	---------------------------

The CO₂ reduction potential was calculated based on the assumption of an average 0.5 h to maximum 4 h per day mill operation with surplus renewable electrical power as a substitute for electrical power produced from fossil fuels. The CO₂ reduction potential refers to an average specific electrical energy demand for raw meal and cement production of 25 kWh/t and 45 kWh/t respectively, with an average mill utilisation factor of 85%.

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Additional production and silo capacities
- Local cement demand
- 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]
2020	30 to 40	decrease 0.17 to 0.34	up to 25	not available
2030	30 to 40	decrease 0.18 to 0.37	up to 25	not available
2050	30 to 40	decrease 0.15 to 0.30	up to 25	not available

Remarks:

- The investment costs for new installations 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. The investment costs for new installations consider high pressure grinding rolls (HPGR) plus ball mill including auxiliary equipment as a hybrid or semi-finish grinding circuit installations
- Investment costs for retrofit installations consider only the additional cost for increased capacities for mills and silos than are normally required for a 6000 tpd plant. The costs for retrofit take into account an additional pre-grinding step with HPGR in front of an existing ball mill
- The reduction of operational costs is calculated based on an estimated power demand of 30 kWh/t for an OPC cement combi-grinding with a target fineness level of 3000 cm²/g acc. to Blaine, an estimated additional power demand for auxiliary grinding equipment of 15%, and an average mill utilisation factor of 85%. It is calculated for new installation only with significantly increased grinding capacity and consequently increased demand side management potential. The reduction of operational costs for new installations is based on an estimated 5% to max.10% cost reduction in electrical energy purchase in the case of demand side management application with one additional mill. It can differ significantly depending on the mill utilisation factor as well as the basic level and volatility of regional electrical energy prices
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Investment and operational costs for unused capacity of mills and silos
- High frequency of power load fluctuations and short forecasting periods
- Efficiency losses by on/off operation (accelerated wear of equipment, maintenance, product with uncertain quality in the case of an increasing number of product changes)
- Low share of renewable energy in electrical energy mix
- Investment in renewable energy production

4.26 Technology Paper No. 26: 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 cement grinding. Ball mills still account for the majority of installed mills 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 combining high pressure grinding rolls (HPGRs) with existing ball mills (retrofit) or by a complete substitution of these ball mills (new installation). The combination of a VRM and ball mill is also possible but rarely implemented.

Theoretically, the specific energy consumption 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. 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 that of ball mills. High-pressure comminution typically results in narrow size distribution, which has to be taken into account 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 more complex grinding system (semi-finish-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 respective investments and requires additional maintenance efforts.

Impact on energy consumption

thermal:	not applicable	electric:	decrease of 6 to 18	kWh/t cem
----------	----------------	-----------	------------------------	-----------

CO₂ emission reduction

direct:	not applicable	indirect:	decrease of 3.8 to 10.1	kg CO ₂ /t cem
---------	----------------	-----------	----------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Clinker properties (grindability)
- Moisture of cement constituents
- Product quality (fineness, PSD)

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	20 to 30	1.0 to 1.7 decrease	4 to 15	up to 1.0 decrease
2030	20 to 30	1.1 to 1.8 decrease	4 to 15	up to 1.1 decrease
2050	20 to 30	0.9 to 1.5 decrease	4 to 15	up to 0.9 decrease

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a
- Investment costs for a new installation are based on the installation of a new vertical roller mill or new roller press to substitute an old ball mill. The investment costs for a retrofit are based on the installation of a smaller roller press as a pre-grinder or together with a new separator as a “semi-finish-grinding-system” with an existing ball mill circuit
- A new installation of a complete “semi-finish-grinding-system” can cost up to 40 Mio €
- The influence of increased maintenance efforts, effects on product quality, additional thermal energy for drying and higher complexity of operation have not been taken into consideration
- Evaluation of reduced energy demand is based on cement grinding only
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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

4.27 Technology Paper No. 27: High efficiency Separators

Open-circuit mills are limited when producing high product fineness and can only achieve this with high power demand. To increase efficiency, mills are connected to adjustable air separators and used in a 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 older separator generations. High efficiency separators contribute to the energy demand for grinding with about 5 to 8%. Even if the energy demand is high, separators have a potential to contribute to an overall energy saving of 10 to 15%. 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 often restricted by limited knowledge of the complex process interactions.

Impact on energy consumption

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

CO₂ emission reduction

direct:	not applicable	indirect:	decrease of 1.3 to 2.5	kg CO ₂ /t cem
---------	----------------	-----------	---------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Clinker properties (grindability)
- Moisture of cement constituents
- Product quality (fineness, PSD)
- CO₂ 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]
2020	1.5	0.2 to 0.4 decrease	1.5	0.2 to 0.4 decrease
2030	1.5	0.2 to 0.5 decrease	1.5	0.2 to 0.5 decrease
2050	1.5	0.2 to 0.4 decrease	1.5	0.2 to 0.4 decrease

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a
- In operating costs the savings in electrical energy are based on application to cement grinding
- Impact on product quality and increased maintenance effort are not considered
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Enhancement of the understanding of the grinding process
- Measurement and control technique
- Measurement expenditure
- Workability of grinding aid

4.28 Technology Paper No. 28: Optimisation of operating 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 installed mills 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 as in many cases no additional capital costs are required. Parameters that hold potential energy savings are the material filling level and ball filling degree, the combination of the ball charge, the liner design, adjustment of intermediate and outlet walls and the adjustments of the separator. Standard optimisation methods include meter sampling along the grinding path as well as separator sampling. By 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 include static electric ears and dynamic electric ears / vibration detectors (mounted on the turning mill shell) 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, 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 consumption

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

CO₂ emission reduction

direct:	not applicable	indirect:	decrease/ increase of 0.3 to 2.0	kg CO ₂ /t cem
---------	----------------	-----------	--	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Clinker properties (grindability, moisture)
- Product quality (fineness, PSD)
- CO₂ 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]
2020	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 0.3 decrease

Remarks:

- The cost estimation is based on time and material needed for the investigation of one mill system. These investigations are commonly described as mill audits. The mill optimisation can be done only once
- A plant with a clinker capacity of 2 mio. t/a is equipped with 2 to 4 mill systems in most cases
- Constant specific costs over time are assumed for consideration of the savings in electrical energy as well as reduced cost for wear
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.29 Technology Paper No. 29: Separate grinding of raw material components

For the preparation of the raw mix for cement clinker production it is typically necessary to add different corrective components in order to adjust the chemical composition of the raw material coming from the quarry. Normally the grindability of the different constituents in the raw mix can vary significantly. Consequently, components which are hard to grind are usually recirculated more often in the mill system to supply sufficient comminution stress within the mill in comparison to easy-to-grind components. This causes an increase of specific energy demand for raw material comminution in total, as well as a reduced throughput rate in the case of combined grinding of all components.

As a consequence, it can be more efficient to grind the raw material components separately. Under the prerequisite that the materials can be sufficiently dried, the separate grinding of large material quantities by high pressure comminution mills can be advantageous in terms of energy efficiency compared to ball mills.

The most common application of this is separate grinding of sand or slag components, which are both much harder to grind and more abrasive than main raw material constituents such as limestone or marl. However, in general only a sufficiently high amount of material of each component justifies the additional effort for the installation of another new mill for separate grinding.

During inter-grinding, softer components might be ground finer than necessary, while more energy is needed for the hard components (often sand as a SiO₂ carrier) to be comminuted. In comparison, separate grinding allows the production of a raw meal with differentiated fineness levels and subsequent optimised mixtures. However, the additional electrical energy demand for blending has to be considered, as well as the need for additional silo capacities. With respect to raw meal burnability, reactivity during the clinkerisation and the formation of silicate crystals, inter-grinding is more advantageous. The influence on burnability behaviour can be a very site-specific effect and difficult to quantify in advance.

Impact on energy consumption

thermal:	not applicable	MJ/t cli	electric:	decrease of 1.0 to 1.2	kWh/t cli
----------	----------------	----------	-----------	---------------------------	-----------

CO₂ emission reduction

direct:	not applicable	indirect:	decrease of 0.6 to 0.7	kg CO ₂ /t cli
---------	----------------	-----------	---------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Properties of raw material from quarry
- Grindability of raw mix components
- Applied grinding technology

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	10 to 20	decrease 0.14 to increase 0.03	2 to 5	decrease 0.13 to increase 0.03
2030	10 to 20	decrease 0.15 to increase 0.02	2 to 5	decrease 0.13 to increase 0.03
2050	10 to 20	decrease 0.13 to increase 0,04	2 to 5	decrease 0.12 to increase 0.04

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a
- Investment costs for retrofit are based on the assumption that grinding equipment and silo capacity for separate grinding are already available
- Investment 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 influence on component wear and an increased energy requirement for transport
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- High investment costs compared to very limited effect if the installation of an additional mill is necessary
- Increase of operational costs can be significantly higher than the savings of costs for electric energy and fuel use in the clinker burning process.
- 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

4.30 Technology Paper No. 30: Advanced grinding

Comminution processes account for up to 70% of the electric energy demand for clinker and cement production. In order to improve the energy efficiency in grinding, high pressure comminution is replacing comminution with single operating ball mills step by step. Nevertheless, the potential for energetic optimisation of grinding equipment with currently available and commonly utilised comminution technology seems to be limited, although theoretically grinding technologies should provide significant saving potentials.

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 examines “Future grinding technologies” for the cement manufacturing process and classifies them in terms of coarse pre-comminution, fine and ultra-fine grinding. It involves cross-sectoral stakeholders including equipment suppliers and highlights technologies of different development stages.

Up-coming challenges of optimising cements with two or more main constituents and the rising demand for increased product fineness emphasise the need for more specialised grinding technologies, flexible plant layouts and blending strategies. Moreover, the requirement to reduce the specific energy demand for comminution and the corresponding indirect emission of CO₂ per tonne cement is affecting future grinding strategies. Based on the classical grinding technologies identified to be sufficient for dry comminution of cement constituents, the ECRA “Future grinding technologies” project provides the basis for new comminution strategies. The concept of energetically improved grinding and mixing of optimised cement particle size distributions (PSDs) can be found in ‘multi-stage grinding’, where all cement main constituents and even raw material for clinker production can be ground to the optimum fineness. This can be realised by implementing various grinding steps. Coarse pre-comminution is predestined for raw material grinding below 200 µm. Fine grinding equipment can be utilised for grinding clinker, slag, limestone and raw material, whereas ultra-fine grinding devices can provide cement main constituents of very high fineness beyond 8000 cm²/g (Blaine). The benefit of a multi-staged grinding plant layout lies in the subsequent blending and homogenisation of the optimal cement PSD and in an increase of the total comminution efficiency at the same time.

Multi-stage grinding on the one hand delivers the key towards utilisation of very efficient grinding equipment in various fineness ranges, but on the other hand depends on the requirements and infrastructure of every single cement plant. Therefore, the concept of multi-stage grinding will be an individual solution for each specific plant. Hence, an estimation of the investment and operational costs cannot be done on this general level.

Impact on energy consumption

thermal:	not applicable	electric:	not available
----------	----------------	-----------	---------------

CO₂ emission reduction

direct:	not applicable	indirect:	not available
---------	----------------	-----------	---------------

Material input

not applicable

Technical Readiness

TRL 2022: 1 applicability for industry at TRL >8 expected around: 2050

The main influencing parameters are

- Properties of cement's main constituents (grindability, moisture)
- Product quality (fineness, PSD)
- Physical limitations for energy transfer
- Material science and grinding technology
- Durability of wear elements
- CO₂ intensity of the power production equivalent to the retrenchment
- R & D efforts

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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.

Conditions, barriers, constraints, enabling framework

- 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
- Technology up-scaling to industrial size with satisfying throughputs and finenesses
- Detailed understanding regarding dry comminution of cement constituents with sufficient and highly efficient technologies required

4.31 Technology Paper No. 31: Separate ultra-fine grinding and blending of cements

Separate grinding and mixing is a commonly used practice in the cement industry to produce energy-efficient multi-composite cements of high quality. Usually, ball mills (BM) are used to grind cements and their main components to high fineness. The resulting particle size distribution (PSD) is comparably broad, which leads to excellent cement properties. Moreover, due to the fact that ball mills are robust and simple to operate, and as the operational experience is high, the use of this comminution technology is still state-of-the-art in the cement industry. Nevertheless, the specific energy demand of ball mills is very high. Through the use of very efficient grinding technologies such as high-pressure grinding rollers (HPGR), the PSD of the product is often very narrow. Moreover, such grinding devices are commonly limited in maximum fineness compared to the BM. This of course affects the cement properties of the ground products. Combined grinding circuits can lead to significant energy savings and broader PSDs, but also increase CAPEX.

Through the use of existing grinding devices and circuits the potential to adjust the PSD is limited. Separate ultra-fine grinding (SFG) can provide a further lever to improve the cement properties. The basic approach of the SFG is to redesign the material flow and to provide a further degree of freedom in order to optimise the PSD and therefore the cement properties.

Compared to a common combi-grinding circuit including a BM, only a small amount of the finest pre-ground product of the high-pressure grinding device (1st grinding step (GS)) is subsequently ground in the 2nd GS using a stirred media mill (SMM).

The differently fine intermediate products (IP) are mixed to produce the final cement. The mixture can be optimised by using an advanced mixing strategy, which ensures an adjustment of the final PSD in order to control the cement properties.

Using the approach of separate ultra-fine grinding and mixing, a significant energy saving potential can be achieved compared to a BM which depends on the final product fineness. The energy saving potential for Portland-Composite-Cements depends on the cement fineness, but is additionally affected by the amount of added clinker substitutes and their grindability. Recently completed research activities on separate ultra-fine grinding and blending of Portland-Composite-Cements have revealed an energy saving potential of up to 25 % compared to co-grinding in a ball mill.

Impact on energy consumption

thermal:	not applicable	electric:	decrease 0 to 14	kWh/t cem
----------	----------------	-----------	---------------------	-----------

CO₂ emission reduction

direct:	not applicable	indirect:	decrease 0.2 to 7.7	kg CO ₂ /t cem
---------	----------------	-----------	------------------------	---------------------------

Material input

not applicable

Technical Readiness

TRL 2022: 4 to 6

applicability for industry at TRL >8 expected about: 2030

The main influencing parameters are

- Properties of clinker and other main constituents
- Portions of the main constituents in the final cement blend
- Grindability of the main constituents
- Grinding technologies used
- Required cement properties
- CO₂ intensity of the power production

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not available	not available	not available	not available
2030	50 to 52	0.4 to 1.2 decrease	25	decrease of up to 1.4
2050	46 to 48	0.5 to 1.1 decrease	21	decrease of up to 1.1

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a, with constant specific costs over time and a cement fineness of 4500 cm²/g (Blaine)
- The cost estimation for a retrofit is based on the assumption that a BM and at least one blending silo are already available
- The cost estimation for a new installation is based on the assumption that a new VRM for each cement component and new fine grinding devices have to be installed
- Depreciation, interest and inflation are not included in the operational costs. No additional personnel costs have been considered. Operational costs refer to cost differences for electric energy
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.32 Technology Paper No. 32: 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 low grindability index (e.g. limestone or clay) accumulate in the fine fraction, while on the other hand constituents which are harder to grind remain in the coarse size fraction of the product. Inter-ground fine particles can contain a high amount of overground particles and agglomerates.

In this context the separate grinding and blending of the main constituents enables a new degree of freedom. This approach opens up the possibility to control the fineness level of main cement components like clinker and other latent hydraulic materials such as granulated blast furnace slag, pozzolana and inert filler constituents in the final particle size distribution (PSD) separately. Since different mill types produce different particle size distributions at various fineness levels, an overall product PSD can be specifically designed by choosing selected mill types for different components and the following adjustment of the mixing process. The optimisation process can focus on

- optimisation of the cement properties, or
- reduction of the specific energy demand, or
- increase of the substitution rate of clinker

Furthermore, the envisaged clinker factor reduction requires an increased application of other supplementary cementitious materials (SCMs). The substitution can be accomplished with components like inert limestone, granulated blast furnace slag, calcined clay and further pozzolanic additives in future composite cement portfolios in order to meet emission reduction targets.

In this context the specific PSD design becomes more important with respect to quality requirements and application cases of different cement products with reduced clinker content.

In particular the production of multimodal composite cements with specified particle size fractions, originating from different material components, promises the exploitation of further qualitative optimisation potential of different cement products. This approach enables the specific reduction of clinker content in the cement by limiting it to certain particle size fractions. In this way the hydraulic potential of clinker can be utilised more efficiently without deterioration of final quality requirements. Separate grinding and mixing is a proven technological approach. The advanced development is therefore focused on the optimisation of PSD composition.

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 170 MJ per ton cement savings) and the electrical energy demand can be reduced depending on the amount of clinker substitution.

Impact on energy consumption

thermal:	decrease of 0 to 170	MJ/t cem	electric:	decrease of up to 0.8	kWh/t cem
----------	-------------------------	----------	-----------	--------------------------	-----------

CO₂ emission reduction

direct:	decrease of 0 to 42	kg CO ₂ /t cem	indirect:	decrease of up to 0.4	kg CO ₂ /t cem
---------	------------------------	---------------------------	-----------	--------------------------	---------------------------

Material input

Increased use of alternative main constituents, numbers not available

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Properties of clinker and other main constituents
- Clinker substitution rate
- Local availability of supplementary cementitious materials
- Grinding technology
- Required cement properties

Cost estimation (based on a reference clinker/cement factor of 95%)

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	3 to 8	decrease of up to 2.3	not applicable	decrease of up to 2.1
2030	3 to 8	decrease of up to 2.3	not applicable	decrease of up to 2.1
2050	3 to 8	decrease of up to 2.2	not applicable	decrease of up to 2.0

Remarks:

- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- The cost estimation is based on a clinker capacity of 2 Mio. t/a
- The cost estimation for a 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
- Operational costs include the cost difference for electrical energy. The savings in operational costs are based on an estimated clinker substitution rate of 5% with other SCMs based on a reference clinker/cement factor for OPC of 95%
- No additional labour costs have been considered

4.33 Technology Paper No. 33: 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) which are added in small quantities to the mill feed. Especially with increasing product fineness it is essential during comminution to not only produce additional particle surfaces, but also to control agglomeration mechanisms. 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 neutralising effect on the surface charges. Although they do not actively contribute to particle breakage, their use increases process efficiency by avoiding the formation of coatings and enhances material transport and separator efficiency. But grinding aids can also alter the particle size distribution (PSD) of the product and can have an impact 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 on or inside of grinding devices. But since the residence time in the mill and also the separator performance changes, the PSD is altered, leading to changed product properties. Improved PSDs allow 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 as well as the optimisation of the cement grinding process and the product, a saving potential of 2 to 5 % is expected. A positive effect on raw material grinding is expected to be much lower compared to finish grinding of cement and is therefore not often realised in practice.

Impact on energy consumption

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

CO₂ emission reduction

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
--------------	--	--	--	------------------	---------

Technical Readiness

TRL 2022: 9

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, dosage and concentration of available grinding aid

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	not applicable	0.05 to 0.21 decrease
2030	not applicable	not applicable	not applicable	0.05 to 0.23 decrease
2050	not applicable	not applicable	not applicable	0.04 to 0.18 decrease

Remarks:

- The cost estimation is based on a clinker capacity of 2 Mio. t/a and 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
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.34 Technology Paper No. 34: Reduction of clinker content in cement by use of granulated blast furnace slag

Cements containing granulated blast furnace slag (GBFS) are very common. Their production involves blending by the separately ground clinker and GBFS or inter-grinding the two constituents. As compared to Portland cement less clinker is needed per ton of cement, CO₂ 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 due to savings in clinker production. The thermal energy demand of the cement production decreases almost linearly with the increasing GBFS proportion in cement.

With increasing amount of GBFS, the early strength of cements generally decreases. GBFS in cement can lead to higher long-term strength and higher resistance to chloride ingress. It reduces the risk of alkali-silica-reaction and also increases the resistance against sulphate attack. Cements with higher amounts of GBFS are often used for massive constructions due to lower heat of hydration.

Many cement standards worldwide allow for the use of GBFS as a main constituent in cement. In Europe, the European standards EN 197-1 and -5 define 14 cement types with up to 95 mass-% GBFS. Several main constituents can be combined with GBFS in (Portland) composite cements. Presently, the technical performance and the application of cements with low clinker contents and combinations of GBFS with other main constituents such as clays and/or limestone are being investigated and proposed for a broader application. In practise, today 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. In 2020, an estimated amount of 400 Mio. t of blast furnace slag was produced worldwide of which around 300 Mio. t were granulated to produce GBFS. The amount of steel slag was estimated at 200 Mio. t in 2020.

In the medium term, blast furnace slag and fly ash can be used in ternary and quaternary mixes with steel slag / acidic blast furnace slag and clinker to overcome the lack of hydraulicity of certain slag types, and to increase the availability of slags. Research on this is ongoing.

In the long-term, pig iron production will be increasingly shifted to the Direct Reduced Iron-process (DRI) with hydrogen in the context of global decarbonisation. This is expected to lead to a significant decline in the available quantities of blast furnace slag. Findings on the properties of the resulting DRI-slag and its suitability as a cement component are not yet available. Intensive research is currently being carried out on this.

Impact on energy consumption

thermal: decrease of up to 2514 MJ/t cem compared to Portland Cement	electric: increase of up to 19 kWh/t cem compared to Portland Cement
--	--

CO₂ emission reduction

direct: decrease of up to 629 kg CO ₂ /t cem compared to Portland Cement	indirect: increase of up to 10.6 kg CO ₂ /t cem compared to Portland Cement
---	--

Material input

granulated blast furnace slag	amount of material up to 0.80 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]
2020	not applicable	not applicable	5 to 10	decrease up to 11 compared to Portland Cement
2030	not applicable	not applicable	5 to 10	decrease up to 11 compared to Portland Cement
2050	not applicable	not applicable	5 to 10	decrease up to 11 compared to Portland Cement

Remarks:

- The estimations on impact on energy consumption, CO₂ savings as well as costs and investments are based on GBFS content in cement of 80 mass-% in comparison to the reference plant data (see “key assumptions” in Annex).
- Capital expenditures 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 very much on the purchase costs of GBFS as compared to the cost of clinker production at the site under question. Influencing factors are therefore fuel costs for clinker production, electricity costs for kiln drives and bypass,

electricity costs for raw material and cement grinding, fuel costs for drying of GBFS. An important factor are also logistic costs to transport GBFS to the cement plant

- These costs need to be assessed on the basis of individual plants and cement types. All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints

- Availability (depends mainly on the level of raw iron production, level of slag granulation, and the 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

4.35 Technology Paper No. 35: Reduction of clinker content in cement by use of natural pozzolanas

Pozzolanic materials can be used as main constituents in cement. In replacing clinker they reduce the CO₂ emissions of the cement which result from fuel combustion and from the decarbonation of limestone during clinker production.

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. As an indicator for its reactivity the content of reactive silica is important. As an example, the European cement standard EN 197-1 requires the content of reactive silicon dioxide to be at least 25 mass-%. However, the reactive 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 the crushing, drying and grinding and the intergrinding or mixing of the cement clinker with the pozzolanic material. The electric energy consumption is assumed to be slightly lower because of the better grindability of most pozzolanas compared to the replaced clinker. The thermal energy consumption of the cement production decreases almost linearly with an increase in the pozzolanas. The partly vastly different properties of the cement are disregarded in this approach.

Cement properties vary 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 - and under the same conditions of cement fineness - the early compressive strength of cement decreases with increasing the amount of natural pozzolanas. On the other hand, the use of pozzolanas as a main constituent can lead to better workability, higher long term strength, improved chemical resistance and less efflorescence of concrete products.

The use of natural pozzolanas as a main constituent of cement is common, e.g. in Europe. According to EN 197-1, the production of various cement types containing natural pozzolanas from 6 to 55 mass-% is possible. In practise, the proportion of pozzolana in technically used cements is usually in a range of up to 35 mass-%.

The availability of pozzolanas mainly depends on the local geological conditions. Reliable data on the current worldwide production or which proportions are used as cement constituents are difficult to derive. As a rough estimation, the amount used for cement and concrete was probably around 20 Mio. t in 2020. However, natural pozzolanas and in particular natural calcined pozzolanas will play an important role in lowering the clinker factor in tomorrow's cements.

Impact on energy consumption

thermal:	decrease of up to 1006	MJ/t cem	electric:	decrease of up to 15	kWh/t cem
----------	------------------------	----------	-----------	----------------------	-----------

CO₂ emission reduction

direct:	decrease of up to 251	kg CO ₂ /t cem	indirect:	decrease of up to 8.45	kg CO ₂ /t cem
---------	-----------------------	---------------------------	-----------	------------------------	---------------------------

Material input

natural pozzolanas	up to 0.35	t/t cem
--------------------	------------	---------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

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

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	8 to 12	up to 5.8 decrease
2030	not applicable	not applicable	8 to 12	up to 6.3 decrease
2050	not applicable	not applicable	8 to 12	up to 6.0 decrease

Remarks:

- The estimations on impact on energy consumption, CO₂ savings as well as costs and investments are estimations based on pozzolana content in cement of 15 to 35 mass-% in comparison to the reference plant data (see “key assumptions” in Annex).
- 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 pozzolana.
- 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 through the transport costs of the pozzolanitic material
- These costs need to be assessed on the basis of individual plants and cement types.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints

- Sources, availability (landscape design, competitive use), 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

4.36 Technology Paper No. 36: Reduction of clinker content in cement by use of natural calcined pozzolana

The production of cements containing natural calcined pozzolanic materials reduces the amount of clinker needed for cement production. Thus, CO₂ emissions from fuel combustion and from decarbonation of limestone during clinker production can partially be saved, but must be rated against CO₂ emissions from calcinating the pozzolana. Calcined clays can be used as a cement constituent according to different cement standards worldwide, e.g. EN 197-1 up to 55 mass-% (CEM IV/B). In practise the proportion of calcined clays in technically used cements is usually in a range of 15 to 35 mass-%. In particular, combinations of calcined clays with other cement constituents, e.g. limestone has synergistic effects leading to positive cement properties.

Natural calcined pozzolanas used for cement production are usually thermally activated clays (calcined clays). Depending on their chemical and mineralogical composition, the clays must be heated to temperatures of over 600 °C in order to achieve their pozzolanic potential. During the calcination the structure of the clay minerals decomposes through the release of physically and chemically bound water. 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 (CASH-phases). The reactivity of the calcined product can be determined by means of several methods acc. ASTM C1897-20 or acc. EN 197-1 or determination of an activity index relative to a standard cement or others. The reactive silicon dioxide acc. EN 197-1 does not always correlate with the calcined clays' contribution to the strength of the cement. Furthermore the application of the criterion of at least 25 wt.-% reactive silicon dioxide may exclude clay qualities that are actually suitable for cement production. The methods of ASTM C1897-20 allows a much more differentiated assessment of the clay reactivity. For economical and ecological reasons, in particular clays of lower grade, such as mixtures of several clay minerals, will be of relevance as cement main constituents.

The production of cements with calcined clay involves the pretreatment of the clay, for instance drying (release of up to 30 mass-% water), crushing and calcination, followed by intergrinding or mixing of the cement clinker with the calcined clay. Besides CO₂ emissions from the thermal energy consumption for calcination, decarbonation of carbonate impurities in the raw clays might also be considered at temperatures above 800 °C. The calcination of clays has so far mostly been carried out in rotary kilns, but several flash calciners now already exist. The thermal energy requirement and CO₂ emissions for a calcination at about 800 °C can range between 1 and 2.6 MJ/kg or 0.1 and 0.3 kg CO₂ per kg calcined clay, depending on the type of calcination and the clay moisture content. In principle, calcination in flash calciners appear to be more efficient than calcination in the rotary kiln, both in terms of energy and CO₂ emissions. Depending on the clay composition, for example ammonia, organic or sulphur compounds may be contained in the flue gases, which may require additional flue gas cleaning. Especially against the background of waste heat utilisation and the use of existing plant components, a process-integrated calcination of clay, e.g. in a cement plant itself, appears particularly advantageous. In this heat from the clinker burning process can be taken for calcining the clays while the flue gas from the grinding/drying/calcining process is fed into the kiln inlet of the clinker process to remove unwanted gaseous compounds from clay, so that separate flue gas cleaning might be avoided.

Depending on the manufacturing process and the clay mineral type, the specific surface area of the calcined clay varies. The color of calcined clays can be controlled via adjustment of the cooling conditions. The reddish color (formation of hematite) can be largely avoided if the clays are cooled under a reducing atmosphere (stabilisation of grey magnetite).

The electric energy consumption is assumed to be slightly lower compared to clinker because of the better grindability of calcined clays, which is comparable to the grindability of limestone.

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. According to their fineness and their specific surface area, calcined clays could increase the water demand of the respective cement, which can be compensated by concrete technology measures. On the other hand, concretes with calcined clay cements may show higher long term strength and improved durability due to a dense microstructure.

So far natural calcined pozzolana are commonly used in cement only in a few countries but the demand will significantly increase. Against this background, some flash calciners and rotary kilns for the production of calcined clays are currently being built or planned. In the medium-term the use of calcined clay cements will grow, first of all in areas where no suitable amounts of other reactive cement constituents (slags or fly ashes) are available. In the long-term view, calcined clays are seen as an important material group worldwide to lower the clinker factor in particular 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.

Impact on energy consumption

thermal:	decrease up to 550 compared to Portland Cement	MJ/t cem	electric:	decrease of up to 15 compared to Portland Cement	kWh/t cem
----------	--	----------	-----------	--	-----------

CO₂ emission reduction

direct:	decrease of up to 205 compared to Portland Cement	kg CO ₂ /t cem	indirect:	decrease of up to 8 compared to Portland Cement	kg CO ₂ /t cem
---------	---	---------------------------	-----------	---	---------------------------

Material input

calcined clays (natural calcined pozzolana)	up to 0.35	t/t cem
--	------------	---------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Type, availability, quality and price (incl. logistics) of the raw material (clay)
- Treatment and calcination costs
- Amount of pozzolana in cement
- CO₂ intensity of clinker production
- Transport distances of the raw material

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment ¹⁾ [Mio €]	Operational ²⁾ [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	20 to 40	decrease up to 4.2 € compared to Portland Cement	not available	decrease up to 4.2 € compared to Portland Cement
2030	20 to 40	decrease up to 4.5 € compared to Portland Cement	not available	decrease up to 4.5 € compared to Portland Cement
2050	20 to 40	decrease up to 3.6 € compared to Portland Cement	not available	decrease up to 3.6 € compared to Portland Cement

¹⁾ higher costs if additional flue gas cleaning needed

²⁾ materials costs for raw clays equivalent to raw meal

Remarks:

- The estimations are based on a content of calcined natural pozzolana in cement of 35 mass-% in comparison to a Portland Cement with 95 mass-% clinker
- Capital costs are due to extra storage capacity for the calcined pozzolana and the cements as well as the technical equipment for handling and drying of the calcined pozzolana
- Additional costs for fuels and technical equipment for clay calcination; savings possible, if calcination process-integrated using available plant components
- Depending on the sulfur content of the clay, additional flue gas cleaning will be necessary; savings possible, if process-integrated calcination is used
- 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 could be less due to transport costs of the pozzolanic materials

- For retrofits existing equipment such as rotary kilns can be used in specific cases. Since this is very plant specific and very much depending on the situation on site no investment figures were given for retrofit scenarios.
- These costs need to be assessed on the basis of individual plants and cement types
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.37 Technology Paper No. 37: Reduction of clinker content in cement by use of limestone or other materials

A very simple and efficient method to reduce the clinker content in cement is the use of limestone as a main constituent. Limestone is usually located at the plant in sufficient qualities and quantities. Neither burning nor decomposition is necessary for the use of limestone as a cement main constituent. Therefore, as compared to clinker, limestone exhibits no CO₂ emissions from fuel combustion and decarbonation. The grindability of limestone is much better compared to clinker.

Limestone-containing cements typically show reduced water demand leading to better workability of concrete. To achieve the same strength as Portland cement, limestone-containing cements typically have to be ground finer. The proportion of limestone in cement and the cement content in concrete are decisive for the concrete's resistance to carbonation, chloride ingress, freeze-thaw etc. Cement standards therefore limit the limestone content. The European cement standard EN 197, as an example, limits the proportion of limestone in cement to 35 mass-%. Notwithstanding, higher amounts of limestone in cement up to 50 mass-% are possible (Technology Paper No. 43). This not only requires sophisticated process engineering measures in the cement plant, but also concrete technology measures to lower the water content by appropriate addition levels of admixtures. Special care and quality measures also have to be provided at the construction site to ensure a good robustness of these systems under practical conditions.

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, the European cement standard EN 197, as an example, 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, palm oil ash or cassava peel ash generally have a limited availability but can be of local relevance. The suitability of further industrial by-products, residues and recyclates that could basically react like pozzolans has been under research for several years. Recycled concrete fines will play a growing role, e.g. up to 20 mass-% in cement are suggested in the upcoming part 6 of the European cement standard EN 197 (Technology Paper No. 45). Until now, the limiting factor of these cement constituents has always been the worldwide availability in sufficient and also consistent 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. However, suitable raw shale is available only in some regions.

Impact on energy consumption

thermal:	decrease of up to 1006 compared to Portland cement	MJ/t cem	electric:	decrease of up to 15 compared to Portland cement	kWh/t cem
----------	--	----------	-----------	--	-----------

CO₂ emission reduction

direct:	decrease of up to 251 compared to Portland cement	kg CO ₂ /t cem	indirect:	decrease of up to 8.3 compared to Portland cement	kg CO ₂ /t cem
---------	---	---------------------------	-----------	---	---------------------------

Material input

unburnt limestone	0.3	t/t cem
-------------------	-----	---------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Type, availability, quality and price (incl. logistics) of these cement constituents
- Durability of concrete produced with respective cements
- Impact on electric energy demand and indirect CO₂ emission strongly depends on the properties of the respective materials
- CO₂ 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]
2020	not applicable	not applicable	8 to 12	6 to 8 decrease compared to Portland cement
2030	not applicable	not applicable	8 to 12	6 to 8 decrease compared to Portland cement
2050	not applicable	not applicable	8 to 12	6 to 8 decrease compared to Portland cement

Remarks:

- The estimations are based on the reduction of clinker content from 95 mass-% in reference Portland cement by use of 0.3 t unburnt limestone per t cement to 65 mass-% in limestone-containing cement (see “key assumptions” in Annex).
- Capital costs are due to extra storage capacity for ground limestone and the cements as well as the technical equipment for handling.
- Additional cost that will occur for concrete production have not been included.
- Cost estimations are based on the assumption of keeping the limestone-containing cement fineness the same (maximum decrease in operational cost retrofit) or increasing the limestone-containing cement fineness (minimum decrease in operational cost retrofit) to achieve comparable strength as Portland cement.

- Operational cost savings depend on the purchase costs of the other main constituents, fuel costs for clinker production, 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.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.38 Technology Paper No. 38: Cements with very high limestone content

Clinker-efficient cements have been used for many years very successfully and are increasingly replacing Portland cement. However, in the context of decarbonising the cement and concrete value chain, the question arises as to how the clinker content in cements can be further reduced and which materials will be available in the future to replace clinker. For approx. 30 years limestone has been not only the essential raw material for the production of Portland cement clinker, but is also used (unburnt) as a main cement constituent. Today, typically limestone cements contain no more than 15 mass-% limestone (often much less). Particularly in view of the expected decline in the availability of today's predominantly used cement constituents, such as granulated blast furnace slag and fly ash (as a result of the DRI process in the steel industry or the switch to renewable energies), the further necessary reduction of the clinker factor in cements is a special challenge.

Against this background, the production and use of clinker-efficient cements with high limestone content will play an increasingly important role in the future. On a European level CEM II and CEM VI allow the clinker content to be reduced to 50 mass-% and 35 mass-% respectively. The limestone content is limited to a maximum of 35 mass-% in CEM II/B or even only 20 mass-% in CEM II/C and CEM VI cements, depending on the cement composition. Both cement types enable a low CO₂ footprint and can be used for a very wide range of applications in practice in terms of concrete performance as well as structural suitability.

In terms of the very good availability of limestone and experience about its influence on cements, the further increase of the limestone content in cement in combination with concrete technology adaptations is a very interesting approach for additional CO₂ savings. Tests and first practical experience have shown that it is possible to produce cements with significantly higher contents of unburnt limestone (for example 35 to 50 mass-%). In order to ensure suitable durability properties, the water/cement ratio in the concrete must be significantly lowered and superplasticizers must be used to ensure adequate concrete workability. This is not fundamentally new, as the handling of superplasticisers (high-strength concretes) and the consistencies to be expected have been researched for a long time and have also been used for many decades. Rules for application of those cements are currently being developed so that the first trials in construction practice can begin soon.

Impact on energy consumption

thermal:	decrease of up to 1500 compared to Portland Cement	MJ/t cem	electric:	decrease of up to 15 compared to Portland cement	kWh/t cem
----------	--	----------	-----------	--	-----------

calculated for a cement with 50 mass-% unburnt limestone

CO₂ emission reduction

direct:	decrease of up to 375 compared to Portland Cement	kg CO ₂ /t cem	indirect:	decrease of up to 8.5 compared to Portland Cement	kg CO ₂ /t cem
---------	---	---------------------------	-----------	---	---------------------------

calculated for a cement with 50 mass-% unburnt limestone

Material input

Unburnt limestone	up to	0.5 t/t cem
-------------------	-------	-------------

Technical Readiness

TRL 2022: 5 (e.g. cements with high limestone contents) to 8
applicability for industry at TRL >8 expected about: 2025

The main influencing parameters are

- Change in building traditions
- Increased communication between building clients, architects, planners and construction industry
- Quality requirements at the construction site

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not applicable	not applicable	8 to 12	decrease up to 11 € compared to Portland Cement
2030	not applicable	not applicable	8 to 12	decrease up to 11 € compared to Portland Cement
2050	not applicable	not applicable	8 to 12	decrease up to 11 € compared to Portland Cement

Remarks:

- The estimations are based on the reduction of clinker content from 95 mass-% in reference Portland cement by use of 0.45 t unburnt limestone per t cement to 50 mass-% in limestone-containing cement (see “key assumptions” in Annex).
- Capital costs are due to extra storage capacity for ground limestone and the cements as well as the technical equipment for handling.
- Depending on the fineness of the ground clinker the savings in operational costs reduce to the lower side of the range given.
- Additional cost that will occur for concrete production have not been included.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Change in building traditions (for use of cements with clinker content below CEM II/C)
- Change in standards and regulations

4.39 Technology Paper No. 39: 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 clinker with very high LSFs of more than 100 leads to increased CO₂ emissions due to the calcination of higher amounts of CaCO₃ in the raw meal as well as higher burning temperatures required for such raw meals. Also, the energy demand in the grinding process is higher due to denser microstructures of the clinker granules. Additionally, higher amounts of 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.

Clinker with lower LSFs can be produced with lower limestone content in the raw meal, thereby reducing the CO₂-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 variation of the LSF can principally be done by every clinker producer from a technological point of view. However, the economic implementation depends on the actual availability of suitable raw materials. If the clinker producer has such materials, the raw meal cost will not be different from his usual raw meal cost. If he has to buy such materials, the raw meal cost will increase with the according transport costs.

The following estimations are based on a decrease in clinker LSF by 5 units. Full availability of suitable raw materials is assumed.

Impact on energy consumption

thermal:	decrease of 58 to 60	MJ/t cem	electric:	increase of 4 to 12	kWh/t cem
----------	-------------------------	----------	-----------	------------------------	-----------

CO₂ emission reduction

direct:	decrease of 9	kg CO ₂ /t cem	indirect:	increase of 2 to 7	kg CO ₂ /t cem
---------	---------------	---------------------------	-----------	-----------------------	---------------------------

Material input

Raw meal with LSF reduced by 5 units	nearly same amount (1.54)	t/t cli
--------------------------------------	------------------------------	---------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Decrease of the CO₂ releasing component (CaCO₃) 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]
2020	not applicable	not applicable	not applicable	2.2 to 2.9 increase
2030	not applicable	not applicable	not applicable	2.2 to 2.9 increase
2050	not applicable	not applicable	not applicable	2.1 to 2.7 increase

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.
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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

4.40 Technology Paper No. 40: Recycled concrete fines as a cement constituent

Against the background of the expected reduction in the availability of granulated blast furnace slag and fly ash and the need to further reduce the proportion of clinker in cement, new cement constituents, such as calcined clays, but also an increased use of limestone are coming into focus. In addition, it is necessary to explore further sources of adequate quantities of materials that are as reactive as possible (pozzolanic or latent-hydraulic) and suitable as clinker substitutes.

Recycled concrete fines, which are produced during the crushing and processing of concrete (described in Technology Paper No. 40) are a promising new material source for cement production. Ground recycled concrete fines are particularly suitable for use as a cement component, but also as a raw meal component for clinker production (Technology Paper No. 20). Primarily, ground recycled concrete fines can be used as a substitute for limestone in composite cements without further processing.

Via enforced carbonation, remaining $\text{Ca}(\text{OH})_2$ and CSH-phases in the recycled concrete fines can be carbonated and a pozzolanic reactivity can be generated by the formation of an amorphous aluminosilicate gel (Technology Paper No. 55). Such a material can be used as a reactive supplementary cementitious material (SCM) in composite cements comparable to fly ash. It improves, among other things, the strength development of cements, even at early ages. In addition, carbonation causes microstructure densification (see Technology Paper 60), which can have a positive effect on the water demand of the fines. Depending on the origin and treatment of the waste concrete, recycled concrete fines can have e.g. higher chloride or sulphate contents which must be taken into account when using them as a cement constituent.

There are already some technical approvals for cements with recycled concrete fines to be used in concrete. A European Standard (prEN 197-6) is currently being prepared which regulates the requirements for cements with recycled concrete fines as a cement constituent. According to this draft, recycled fines from mineral construction waste can be used in Portland-composite cements up to 20 mass-%. Higher input quantities, especially of pozzolanic recycled concrete fines, are quite feasible if the respective durability aspects of concrete are adapted accordingly.

The use of (carbonated or uncarbonated) recycled concrete fines as a cement constituent is a key additional element on the way to the circular economy of cement and concrete, because these materials can be used in cement as a (possibly pozzolanic) cement constituent to reduce the clinker factor and to replace primary resources like e.g. (unburnt) limestone.

For regions with an average stock of concrete structures, it can be assumed that the usual demolition quantities of concrete and the resulting quantities of recycled concrete fines should be high enough to replace the limestone content in composite cements to a large extent.

Challenges are certainly the large quantities of material to be handled. For one tonne of recycled concrete fines, about 3 tonnes of crushed concrete have to be processed. Currently, crushed concrete from constructions is hardly being used for the production of cement and concrete. Rather, almost all of the processed crushed concrete quantities are used for road substructures or are mixed with soil material to improve its properties (e.g. for frost protection

layers). Compared to the existing recycling practice of concrete, new source streams must be initiated which take into account the complete reuse of the crushed concrete for the production of new fresh concrete (recycled aggregate), as well as for clinker and cement production (recycled concrete fines, cement paste). Furthermore, a corresponding infrastructure for the processing of crushed concrete, an adequate quality assurance and a transport system for the respective source streams must be established. The technical potential of these materials is the subject of current research.

Analogous to recycled concrete fines, waste bricks in finely ground form are also suitable as a cement constituent. Intensive research is also being carried out on this.

The estimations below are based on the reduction of clinker content from 95 mass-% in reference Portland cement to 75 mass-% using enforced carbonated recycled concrete fines in composite cements. Further assumptions:

- proportion of cement paste in recycled concrete fines (50 mass-%)
- proportion of cement (Portland cement with 95 mass-% clinker) in cement paste (w/c = 50%)
- CO₂ uptake to an amount of 20% of process CO₂ from clinker production via natural carbonation during service life
- remaining carbonation potential used by **enforced carbonation**

Impact on energy consumption

thermal:	decrease of 670	MJ/t cem	electric:	increase up to 23	kWh/t cem
----------	-----------------	----------	-----------	-------------------	-----------

CO₂ emission reduction

direct:	decrease of 184	kg CO ₂ /t cem	indirect:	increase of 13	kg CO ₂ /t cem
---------	-----------------	---------------------------	-----------	----------------	---------------------------

Material input

enforced carbonated recycled concrete fines	amount of material 0.2	t/t cem
---	------------------------	---------

Technical Readiness

TRL 2022: 6 (enforced carbonation) applicability for industry at TRL >8 expected around: 2030

The main influencing parameters are

- Composition of recycled concrete fines; clinker and cement content, cement type (e.g. limestone in cement paste reducing the carbonation potential)
- Carbonatisation degree of (CO₂ untreated) recycled concrete fines
- Amount of carbonatable cement paste
- Extent of natural carbonation vs. CO₂ that can be re-incorporated via enforced carbonation
- Substitution rate of clinker
- Grindability of recycled concrete fines

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not available	not available	not available	0.3 increase to 2.3 decrease
2030	not available	not available	not available	0.3 increase to 2.3 decrease
2050	not available	not available	not available	0.3 increase to 2.3 decrease

Remarks:

- see comments above the tables
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Currently, crushed concrete from constructions is hardly used for the production of cement and concrete; Mainly used for road substructures
- Processing (separation, crushing, fractionation etc.) of crushed concrete must be improved in order to obtain recycled concrete fines; Source stream must be established
- Long transport distances from demolition site (processing) to CO₂ treatment and cement production
- Systems for enforced carbonation must be further developed, especially in existing cement plants for the use of flue gases (higher CO₂ uptake, lower retention time)
- Carbonation potential mainly depends on calcium-containing phases in cements such as clinker, slag etc.
- Corresponding infrastructure for processing of waste concrete, an adequate quality assurance and transport systems must be established

The estimations below are based on the reduction of clinker content from 95 mass-% in reference Portland cement to 75 mass-% using recycled concrete fines (**not enforced carbonated**) in composite cements.

Impact on energy consumption

thermal:	decrease of 670	MJ/t cem	electric:	increase up to 23	kWh/t cem
----------	-----------------	----------	-----------	-------------------	-----------

CO₂ emission reduction

direct:	decrease of 170	kg CO ₂ /t cem	indirect:	increase of 13	kg CO ₂ /t cem
---------	-----------------	---------------------------	-----------	----------------	---------------------------

Material input

recycled concrete fines	amount of material	0,2 t/t cem
-------------------------	--------------------	-------------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Substitution rate of clinker
- Grindability of recycled concrete fines

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	not available	not available	not available	0.3 increase to 3.0 decrease
2030	not available	not available	not available	0.3 increase to 3.0 decrease
2050	not available	not available	not available	0.3 increase to 3.0 decrease

Remarks:

- see comments above the tables
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- Currently, crushed waste concrete from constructions is hardly used for the production of cement and concrete; Mainly used for road substructures
- Processing (separation, crushing, fractionation, etc.) of waste concrete must be improved in order to obtain recycled concrete fines; source stream must be established
- Long transport distances from demolition site to cement production
- Corresponding infrastructure for processing of waste concrete, an adequate quality assurance and transport systems must be established

4.41 Technology Paper No. 41: Reduction of clinker content in cement by use of fly ash

The production of cements containing fly ashes leads to a reduced clinker content of the cement. CO₂ emissions from fuel combustion and from decarbonation of limestone during clinker production can therefore be partially saved.

Fly ash is obtained by the 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 which have pozzolanic properties; the latter may have, in addition, hydraulic properties. Siliceous fly ash consists essentially of reactive silicon dioxide (SiO₂), aluminium oxide (Al₂O₃) and calcareous fly ash of reactive calcium oxide (CaO), reactive silicon dioxide (SiO₂) and aluminium oxide (Al₂O₃). In particular calcareous fly ashes may have critical sulfate (SO₃) 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 around 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 CO₂ footprint of concrete. 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. Currently about 600 Mt/a of fly ash are produced worldwide. With respect to decarbonisation, the future number and capacity of coal fired power plants is hard to predict. Based on the predictions of energy production from coal in the IEA roadmap for the global energy sector, around 300 Mt/a of fly ash can be expected for 2030 and less than 100 Mt/a for 2050.

The ratios of fly ash utilisation in cement and concrete differ strongly in different countries or regions (China ~45%, India ~38%, USA ~65%, up to 100 % in several EU countries).

The following estimations are based on fly ash contents in cement of 35 mass-% in comparison to Portland Cement (95% clinker).

Impact on energy consumption

thermal:	decrease of up to 1000 compared to Portland Cement	MJ/t cem	electric:	decrease of up to 8 compared to Portland Cement	kWh/t cem
----------	--	----------	-----------	---	-----------

CO₂ emission reduction

direct:	decrease of up to 250 compared to Portland Cement	kg CO ₂ /t cem	indirect:	decrease of up to 4 compared to Portland Cement	kg CO ₂ /t cem
---------	---	---------------------------	-----------	---	---------------------------

Material input

coal fly ash	up to 0.35	t/t cem
--------------	------------	---------

Technical Readiness

TRL 2022: 9

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]
2020	8 - 12	up to 2.5 decrease compared to Portland Cement	not applicable	up to 2.5 decrease compared to Portland Cement
2030	8 - 12	up to 2.5 decrease compared to Portland Cement	not applicable	up to 2.5 decrease compared to Portland Cement
2050	8 - 12	up to 2.5 decrease compared to Portland Cement	not applicable	up to 2.5 decrease compared to Portland Cement

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, separating, 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, and reduced handling and mining costs

- Grinding the clinker to higher fineness reduces the given savings in operational costs
- These costs need to be assessed on the basis of individual plants and cement types
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

- 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
- The utilisation of fly ash in cement or in concrete: the effects on the specific CO₂ footprint of concrete is in the same order of magnitude for both applications

4.42 Technology Paper No. 42: Reduction of CO₂ by efficient use of concrete

An increased use of clinker-efficient cements in concrete production can save considerable amounts of CO₂ (see Technology Papers No. 34 to 38, 40, 41, 43 to 47 and State-of-the-art Paper No. 4). In addition, CO₂ and primary resources can be saved by optimising the concrete composition including the grading curves of the aggregates. This goes along with a more differentiated use of concrete according to its actual exposure which requires the concretes to be tailored to the respective application instead of being used as "general purpose concretes". For example, different concrete formulations can be used in buildings for interior walls as compared to ceilings or columns. Tailoring such concrete formulations to its specific use will assure the required concrete performance at the lowest possible CO₂ emissions and minimal use of primary raw materials.

While these measures focus on the concrete composition and its performance as such the efficient use of concrete by respective design and construction is an additional and important pathway to save CO₂ and resources. From today's point of view, the following examples are of particular importance:

Prestressed flat or hollow slabs allow to optimise the use of concrete and reinforcement. Prefabricated, prestressed concrete slabs require up to 50 % less concrete and up to 75 % less steel compared to other comparable concrete slab systems with similar technical performance.

Carbon concrete takes advantage of textile and carbon fibres instead of steel as reinforcement material. This increases durability and prolongs the service life of elements and structures, thus saving resources and CO₂ emissions. For structures of equal performance, savings of concrete of up to 50% and CO₂ of up to 30% are reported. A broad application of this type of reinforcement will require the carbon fibres to be less expensive, also its recyclability needs to be further investigated.

Additive manufacturing, often called "3D printing" can help to optimise load-bearing structures with respect to material intensity as well as construction times. At present, there are not enough reliable data and experiences to assess the potentials with regard to resource efficiency and climate protection in detail.

In gradient concrete, the concrete composition is varied over the cross-section of a concrete element. Load-bearing areas are produced with higher density than areas that are intended to meet more thermal requirements such as e.g. insulation. In a similar way, infra-light concretes enable external wall constructions without additional thermal insulation due to their porous aggregate and a correspondingly high air content.

High-strength and ultra-high-strength concretes often contain many fines and usually have a higher density of the concrete microstructure as compared to normal concretes. High strength concretes allow concrete elements to be built with smaller cross-sections and thus reduced material consumption with the same load-bearing capacity compared to normal concrete. This goes along with a respective higher resource efficiency and generally lower CO₂ emissions per structural unit.

With the technologies mentioned here, higher material efficiencies and thus savings in resources, energy and CO₂-emissions can be achieved in certain areas of application. The extent of these effects can only be estimated in detail in real cases with corresponding design and construction parameters.

While the concrete technology and design requirements for the use of such resource-saving components has been tested in pilot projects the application on a broader scale will be possible but still has to be further developed.

Impact on energy consumption

thermal:	negligible	MJ/t cem	electric:	negligible	kWh/t cem
----------	------------	----------	-----------	------------	-----------

CO₂ emission reduction

direct:	not applicable ¹⁾	kg CO ₂ /t cem	indirect:	not applicable	kg CO ₂ /t cem
---------	------------------------------	---------------------------	-----------	----------------	---------------------------

¹⁾ the savings are based on approx. 10 % savings of cement volumes in concrete and approx. 20 % in design and construction respectively. CO₂ savings per tonne of cement is not the right figure in this context.

Material input

common concrete raw materials carbon reinforcement for carbon concrete	amount of material
---	--------------------

Technical Readiness

TRL 2022: 4 (e.g. gradient concrete) to 9 (e.g. prestressed flat or hollow slabs)
applicability for industry at TRL >8 expected about: 2030 to 2050

The main influencing parameters are

- Change in building traditions
- Increased communication between building clients, architects, planners and construction industry
- Increased prefabrication level
- Availability and price of carbon reinforcement
- Increase of digitalisation level, e.g. for 3D printing

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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, enabling framework

- Change in building traditions
- Change in standards and regulations as well as building codes

4.43 Technology Paper No. 43: 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 aluminosilicate 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 aluminosilicates which can be of natural (metakaolin, natural pozzolana) or industrial origin (fly ashes, granulated blast furnace slags - GBFS). The availability of these materials is limited and 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 such as strength development or 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 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 such as paving, tubes, pavers, or refractories. Techniques for the mass production of alkali-activated binders have been suggested, and a first industrial plant has been built in Australia.

An up to “90%” CO₂ 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. The global warming potential can even exceed that of Portland cement concrete. Based on today’s knowledge, the environmental benefit of materials like GBFS or fly ash seems to be higher when used as a clinker substitute in blended cements than the use of alkali-activated binders.

Impact on energy consumption

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
---	---

CO₂ emission reduction

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 applicable 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 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

Remarks:

- Currently no real cost figures are available. These 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, enabling framework

- Properties of alkali-activated binders strongly depend on the starting material properties, so 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)

4.44 Technology Paper No. 44: Cements based on carbonates or 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(hydrates) can also be considered as a possible CO₂ sequestration process, whereby the carbonation of Ca-silicates (e.g. wollastonite, CaO x SiO₂) proceeds much more rapidly. The mechanisms of aqueous wollastonite carbonation have been observed to occur via two steps: (1) Ca leaching from the CaSiO₃ matrix and (2) CaCO₃ nucleation and growth. During the carbonation process the compressive strength rises as a function of time and CO₂-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 x SiO₂) and rankinite (3 CaO x 2 SiO₂) 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 CO₂ emissions in comparison to Portland cement are postulated. This non-hydraulic cement is used for Solidia Concrete, which is composed of the same concrete 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 CO₂ and the calcium silicates during CO₂curing. During carbonation calcium carbonate and amorphous silica (SiO₂) are formed. The processes require a CO₂-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 CO₂ 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 consumption

thermal: not available MJ/t cem	electric: not available kWh/t cem
---------------------------------	-----------------------------------

CO₂ emission reduction

direct: not available kg CO ₂ /t cem	indirect: decrease of 200 to 300 kg CO ₂ /t cem
---	--

Material input

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

The main influencing parameters are:

- Reuse/reconditioning/storage of CO₂ from clinker production
- Relative increase of use of pre-fabricated concrete products, further proof of durability
- Handling of CO₂ during manufacturing (safety at work)
- Development of corrosion-resistant reinforcements could enable use for reinforced concrete elements

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:

- Existing equipment for cement and concrete manufacturing can be used. Set-up of CO₂-curing systems (supply, storage, safety issues, curing chambers etc.) in precast element plants necessary.

Conditions, barriers, constraints, enabling framework

- Set-up of CO₂-curing systems (supply, storage, safety issues, curing chambers etc.) in precast element plants necessary
- Reuse/reconditioning/storage of CO₂
- Extended use of pre-fabricated elements/constructions

4.45 Technology Paper No. 45: 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.

A new approach is the activation of an autoclaved non-hydraulic CHS-precursors such as α - C_2SH phase by grinding in a stirred media mill to calcium-hydrosilicates (hCHS) with hydraulic properties. These properties result more or less from the breakdown of hydrogen bonds during grinding. The hCHS-phases can hydrate with water to calcium-silicate-hydrates (C-S-H), which contribute to strength development. 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 non-hydraulic CHS, e.g. α - C_2SH , and (3) drying and activation grinding of CHS to produce hydraulic hCHS.

There is still a large potential for optimisation, as the principles of activation grinding are very different from the experience with "simple" comminution, e.g. ball mills or vertical mills. 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. As the binder is already pre-hydrated, the water it already contains must be considered in adjusting the w/c ratio. 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 is seen to be advantageous for high durability applications.

A CO_2 saving potential between 30 and 50% compared to average Portland cement clinker is reported. Compared to average global cement composition (clinker-to-cement factor of ca. 72) the saving potential might be correspondingly lower. Currently no real cost figures are available for such a procedure. A first industrial plant with a capacity of 50,000 t/a is planned for 2024/2025.

Impact on energy consumption

thermal: not available MJ/t cem	electric: not available kWh/t cem
---------------------------------	-----------------------------------

CO_2 emission reduction

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 CO₂ emissions by using a precursor material with low Ca/Si ratios and 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 cementitious 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, enabling framework

- 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 Ca(OH)₂ content of the matrix can affect corrosion inhibition of reinforcement, but as the matrix provides a very low permeability it can physically contribute to a corrosion protection

4.46 Technology Paper No. 46: Other low carbonate cements - Belite cements

Ordinary Portland cement (OPC) clinker is produced with an 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 of 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 CO₂/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 CO₂ 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 yet suitable for mass production.

The most important challenge of industrial belite clinkers is the poor hydraulic reactivity of belite compared to alite, leading to a decelerated strength development that is considered unsatisfactory by most customers. The hydraulic hardening can be improved by the addition of Portland cement. 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, as compared to Portland cement, the water/cement ratios in belite cements is lower and the pore structure of hardened concrete can be remarkably denser, leading to a high long term strength and durability. The moderate development of hydration heat makes belite cement suitable particularly for massive concrete structures.

Impact on energy consumption

thermal: decrease of 299 to 365 compared to Portland Cement clinker MJ/t cli	electric: increase of 20 to 40 kWh/t cli compared to Portland Cement clinker
--	--

CO₂ emission reduction

direct: decrease of 48 to 54 kg CO ₂ /t cem compared to Portland Cement	indirect: increase of 10 to 16 kg CO ₂ /t cem compared to Portland Cement
--	--

Material input

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

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Decrease of the CO₂ releasing component (CaCO₃) 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
- CO₂ intensity of fuel use
- CO₂ intensity of electricity consumption

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	similar to standard cement plants	not applicable	not applicable	increase 2.5 to 3.6 compared to Portland Cement
2030	similar to standard cement plants	not applicable	not applicable	increase 2.7 to 3.3 compared to Portland Cement
2050	similar to standard cement plants	not applicable	not applicable	increase 2.3 to 2.8 compared to Portland Cement

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 the 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, and possibly increased electricity costs for the 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 at laboratory-scale
- All other technical and financial assumptions been made are given in Annex I of this document.

Conditions, barriers, constraints, enabling framework

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

4.47 Technology Paper No. 47: Other low carbonate clinkers: (Belite) calcium sulfoaluminate clinker

Calcium sulfoaluminate cements mainly contain the phases ye'elimite or tetracalcium trialuminate sulfate (C_4A_3S), belite (C_2S) and gypsum as well as other phases such as 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.

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. 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 aim 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_3S), calcium aluminoferrites (C_4AF , C_2F), ternesite (C_5S_2) as principal phases and also include certain combinations of minor elements in order to stabilise the belite in the more reactive α' form. During hydration ettringite and aluminium hydroxide ($Al(OH)_3$) (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, 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. Such cements are commercially available. Their application is usually regulated by technical approvals and often limited, e.g. mostly for non-structural concrete elements.

The amounts of bauxite and sulfate needed as raw materials limit the production of BCSA cements to sites where these materials are available at economically viable costs. Other cements like the so-called Porsal cement are also produced with reduced lime contents, but with 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 mineraliser.

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 calcium aluminate sulfate phases and internal recirculating sulfate systems in the kiln.

Impact on energy consumption

thermal: not available MJ/t cli	electric: not available kWh/t cli
---------------------------------	-----------------------------------

CO₂ emission reduction

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 of alumina and sulfate sources at viable costs
- 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 and characteristics of the production process and products do not allow for a consistent quantitative assessement.

Conditions, barriers, constraints, enabling framework

- Limited availability of alumina and sulfate sources
- Economically viable costs for the raw materials
- Lack of experience regarding construction concretes
- Lack of standards and regulations
- Market acceptance

4.48 Technology Paper No. 48: Carbon capture technologies

4.48.1 Introduction

Carbon capture technologies are inevitable to achieve net zero CO₂ emissions in the cement sector by 2050. Various technologies can fulfil the task of separating and purifying CO₂ from flue gases of the cement industry. However, the capture technologies differ in the type of process, level of integration, technical maturity, capture efficiency, energy demand and costs

The decision-making process for an adequate capture technology is complex due to the significant number of site-specific boundary conditions to be evaluated, such as:

- Onsite infrastructure (e.g. power infrastructure)
- Cement plant process technology and condition
- Power and fuel costs
- Availability of excess heat
- Availability of materials
- Space requirements
- Time horizon for project development
- Envisaged amount of captured CO₂
- Access to steam, oxygen, electricity

Most important from a cement producer's point of view is the applicability of a capture technology, its maturity (TRL), the investment needed and the cost to operate.

4.48.2 Methodology and assumptions

The techno-economic assessment as well as the evaluation of the CO₂ reduction potential is based on main assumptions valid for each of the capture technologies, as listed below.

Technical assumptions:

- CO₂ is transport ready (compressed/purified) and of the same purity level to allow for comparison of all capture technologies.
- Additional thermal input for integrated technologies is supplied by using the existing fuel mix for the clinker burning process. Desorption processes for post-combustion technologies like amine scrubbing and TSA require steam, which is most likely produced by natural gas boilers.
- The capture rate depends on the technology used. The maximum capture rate from technical or economic perspective is assumed.
- All other technical assumptions (such as carbon intensity of the grid and the fuel mix) made are given in Annex I of this document.
- Definition of the Technology Readiness Level (TRL) is given in Annex IV of this document.

Assumptions for cost estimation:

- All investment figures and operational costs refer to 2020 as the reference year. Since inflation is difficult to forecast and since it can be very different from region to region, no inflation has been taken into account. As the projects will be completed many years in the future the shown costs and investment figures are mainly to be used as a comparison between the different technologies.

- Production capacity 6,000 t/d, which is expected to be the dominant kiln size in 2050 on a global scale.
- The investment figures given anticipate learning curves for the different capture technologies. They take into account that – depending on the capture technology and its TRL - the first of a kind projects might require higher efforts than those been built after certain experience has been gained. In essence, a learning curve of 1% per year is assumed for the time period 2020 to 2030 for those capture technologies of TRL <8. For higher maturity levels it is not expected that CAPEX costs will drastically decrease after the first industrial applications.
- The figures provided for energy demand, CO₂ emissions, operational costs and capital expenditures are given in comparison to a reference cement plant if not stated otherwise. Thus, the investment figures and the operational costs are given as the difference to the reference plant (“switch cost”): Therefore, operational costs basically comprise variable OPEX (energy and consumables), and CAPEX is for the capture plant only (i.e. in the case of steam generation for amine scrubbing CAPEX is not included; but operational costs for steam import).
- In the case of integrated technologies such as oxyfuel and integrated carbonate looping only the investment for capture related equipment is included into the CAPEX (i.e. the investment for a conventional kiln line is subtracted from the total investment for the integrated capture unit). This approach has been chosen to allow a direct comparison between the different technologies.
- Retrofitting costs for integrated technologies are higher than for new installations due to more compromises which are required with regard to design and technology implementation. Modernised kiln plants are expected to be upgraded to oxyfuel plants in 2030/2050, which will lead to lower retrofitting costs.
- All other financial assumptions (such as fuel and power costs) made are given in Annex I of this document.
- Costs for required emission abatement technologies (for e.g. DeSO_x, DeNO_x) are included depending on the capture technology.
- Cost estimations do not include the costs of decarbonised fuels or carbon neutral electricity.

Scope of cost estimation - uncertainties in investment figures:

The investment costs were estimated for the core equipment of the capture plant. Peripheral units are necessary for capture projects which were not included in the investment costs given in order to allow the comparison of the different technologies. Examples for such site-specific investments are:

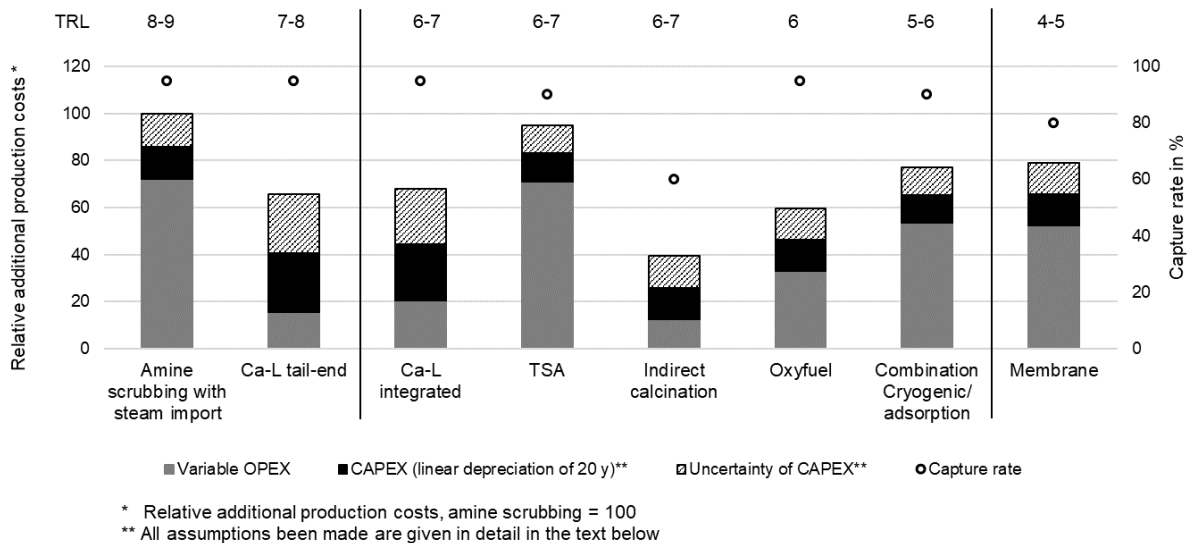
- Onsite intermediate storage of CO₂ or other consumables
- Upgrade of power supply
- Demolishing old equipment
- Water treatment
- CO₂ logistics, transport or storage
- Steam generation
- Provision of required space

Because these site-specific conditions can vary significantly, the given investment volumes (CAPEX) are also subject to a corresponding bandwidth depending on those many plant-

specific factors and circumstances. Furthermore, the location of construction and the technology readiness level (TRL) will influence the estimated costs and its uncertainty. Accordingly, an extended uncertainty of investment figures can be assessed in a range of up to +100%. Further contingencies have not been taken into account.

The following Figure 1 gives a first overview of the additional operational costs for the different capture technologies, their capture rate and their TRL. Detailed information is given in the text which follows.

Figure 1 Comparison of additional production costs, capture rate and TRL of different capture technologies



4.48.3 Technology description

Carbon capture technologies aim at the separation of CO₂ from cement flue gases and their purification to >95 vol.%. In general, the technologies can be grouped into post-combustion (absorption, adsorption, cryogenic and mineralisation processes) and integrated technologies (oxyfuel, integrated Ca-Looping and indirect calcination technology).

Oxyfuel technology

Oxyfuel technology relies on the use of oxygen for combustion instead of ambient air. Due to the removal of nitrogen, the combustion atmosphere in the kiln is dominated by O₂ and CO₂. The amount of oxygen needed requires either an air separation unit (ASU) close to the plant or an oxygen pipeline supply, both state-of-the-art. Replacing conventional ambient air as combustion air by oxygen will result in CO₂ concentrations in the exhaust gas of up to above 80-90 vol.% which allows good CO₂ processing in a capture process. In some important aspects the oxyfuel process is different from conventional operation. In particular this applies to its energy balance, as well as the ratio between the enthalpy flow of the kiln gas and the energy needed for the chemical/mineralogical reactions of the kiln feed.

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. Oxyfuel technology can be implemented by recirculating

part of the flue gases, which does not require any adaptation of plant geometry and allows a relatively easy switch between conventional air and oxyfuel mode.

Oxyfuel technology without flue gas recirculation is referred to as “Pure Oxyfuel”, which operates with lower gas volumes in the kiln system and consequently smaller plant diameters as compared to conventional kilns of similar capacity. Pure Oxyfuel is basically only applicable in new installations. It is expected to result in a higher CO₂ concentration in the flue gas as compared to oxyfuel with flue gas recirculation. Both technologies require the cooler to be re-designed with regard to the supply of cooling gas streams of different composition, covering the challenge of separating them from each other in order to avoid false air intake or CO₂ losses.

For carbon capture the flue gas stream is treated in a CO₂ purification system and a compression facility, resulting in CO₂ which meets the requirements with respect to purity and physical condition for subsequent transport, storage or utilisation. Besides the air separation, the purification step is responsible for a significant increase of electrical energy demand as compared to conventional operation. The achievable CO₂ concentration in the discharged flue gas as a major influencing factor strongly depends on the level of false air leaking into the system. False air could however be reduced to a tolerable level by improved maintenance of state-of-the-art sealings, which is still the most challenging issue for the application of oxyfuel processes.

Both options of oxyfuel technology allow CO₂ capture rates of 90 to 95% to be achieved. A partial approach includes only oxyfuel combustion in the calciner. Whereas this application only requires the redesign of the involved equipment, the capture rate corresponds to up to 75% of the total CO₂ emissions of the kiln.

In the past years a lot of research and prototype testing with regard to operation, clinker quality and equipment re-design has been done on oxyfuel technology in the cement industry. Although not tested completely in pilot scale, oxyfuel technology involves the use of traditional equipment and commercially available units which makes the integration less complicated. The essential pieces of equipment like the burner, calciner and cooler are on a TRL of more than 7. The CI4C consortium envisages the start-up of an oxyfuel demonstration plant located in Mergelstetten, Germany by 2024, lifting the technology to 7-8. First industrial scale plants are planned to start operation from 2028 onwards (projects: K6 project, Carbon2Business, ANRAV), which will pave the way for further commercialisation.

Post-combustion capture using adsorption technology

Absorption techniques are end-of-the-pipe measures for CO₂ abatement. Principally, up to 95% of the CO₂ can be captured with these techniques. After capturing, the CO₂ is purified to > 99% and compressed for transport to a designated destination (storage site or reuse facility). Chemical absorption with alkanolamines is a proven and mature technique in other industry sectors such as the chemical or gas industries. There, flue gas volumes and absorbent cycles are significantly smaller compared to the application in the cement clinker burning process. Alterations are however 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 CO₂ scrubbing. Advanced amines are commercially available, granting lower energy consumption for regeneration. Even more efficient solvents,

based on ammonia or activated potassium carbonate are in the development stage. The chilled ammonia process (CAP) shows a promising approach to these issues but has not been studied for application within the clinker burning process so far.

Due to high cost, the solvents, once they have absorbed the CO₂, have to be regenerated and reused. The regeneration is highly energy consuming. Therefore, the so-called energy or CO₂ penalty is determined by this process. SO₂ and oxygen play an important role in solvent degradation mechanisms, even though the solvents are as stable and insensitive as possible. The absorption technique therefore requires a reduction of SO₂ and particulate matter concentration in flue gases to a minimum (e.g. by wet scrubbers and highly efficient filters). Depending on the initial level, NO_x concentrations have to be lowered as well, as NO₂ can also lead to solvent degradation. On the other hand, NO₂ accounts for only 5 to 10% of total NO_x emissions of cement kilns.

Many CO₂ capture pilot projects with absorption technologies have been carried out in the power sector. Since 2018 the amine scrubbing process has been successfully demonstrated at Anhui Conch plant in Wuhu, China by capturing up to 50,000 t/a CO₂.

A major barrier for a full-scale application is the high thermal energy demand for steam production which is needed for the regeneration of the solvent. Steam can be produced on site requiring respective CAPEX and OPEX or can be bought in requiring respective operational costs only. To lower the overall related capture costs, waste heat from the clinker burning process can be used to cover some of the additional energy required for desorption. However, the degree of waste heat availability is site specific, depending on the raw material moisture, the preheater design and the degree of waste heat already been used for different drying purposes. Further R&D is focussing on developing advanced solvents, which can decrease the additional energy demand for regeneration.

The SkyMine Project combines a scrubbing process and the utilization of CO₂ and is being carried out in the Capitol cement plant in San Antonio (USA). In this process the CO₂ containing flue gas reacts with sodium hydroxide to produce sodium bicarbonate (NaHCO₃). When running at full capacity, the SkyMine plant can capture 75,000 t CO₂/a.

Post-combustion capture using membrane technology

Membranes are being discussed as a future end-of-pipe measure for CO₂ abatement. Principally, more than 80% of the CO₂ can be captured with this technique. After abatement, the CO₂ 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 small scale. Further development is expected to need about 5 to 10 years to reach industrial application. Current research aims to show if 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 CO₂.

Two basic membrane types are being considered for CO₂ capture, namely gas separation (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 similar to 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 of having one component pass through the membrane faster than another (thus driving the separation process). This

technique relies on the diffusivity of gas molecules and takes 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 CO₂ capture have been polymer-based. The second group, gas absorption membranes, are micro-porous solid membranes which act as contacting devices between the gas flow and the 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.

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

Initial trials with flue gas from a cement kiln have been carried out in laboratory scale. A one-stage membrane module with a polyvinyl-based flat sheet membrane was investigated in a six-month test programme. A CO₂ recovery rate of 60 to 70% could be achieved. The results showed that the membrane material could withstand the flue gas from the cement kiln.

As part of the MemCCC project, a membrane-based carbon capture pilot facility was tested for capturing CO₂ from cement flue gases. A specific energy consumption of 1.2 GJ/t CO₂ was assumed for a CO₂ recovery rate of 80% with 95% purity. Another concept, membrane assisted CO₂ liquefaction, was investigated within the CEMCAP project. In this respect, the net power requirement of electrical energy for a capture ratio of 90%, is ca. 1.5 GJ/t CO₂ captured.

Post-combustion capture using physical separation processes

Adsorption and cryogenic processes for CO₂ capture are rapidly developing and could be available on industrial level in the short term. Adsorptive capture processes are based on physisorption on surfaces of solid materials like carbon materials, zeolites, alumino-phosphates or metal organic frameworks (MOFs). Within the reactor, the basic steps of CO₂ adsorption by van-der-Waals forces and desorption forced by either temperature (temperature swing adsorption, TSA) or pressure (pressure or vacuum swing adsorption, PSA/VSA) difference is repeated.

Basically, the energy penalty of adsorption processes could be lower than for chemical post-combustion technologies like amine scrubbing. The technological readiness strongly depends on the sorbent used, which is steadily being improved in terms of sensitivity towards impurities, CO₂ capture rate and achievable CO₂ purity.

Different types of reactor designs can be used. In 2019 Svante installed a pilot TSA process with a capacity of 1 t CO₂/d. Svante's Veloxotherm rotary adsorber can be filled with different types of solid sorbents. Compared to chemical post-combustion technology the CO₂ footprint

is lower. Based on the successful pilot operation the maturity of TSA technology is rated as TRL 7. The thermal energy for regeneration depends on the solid sorbent used and can vary from 1.7 to 3.5 GJ/t CO₂. Reducing the energy penalty is the subject of the current R&D efforts.

Today the CO₂ recovery by means of stand-alone PSA processes depends on the number of beds in a row. Combination of cryogenic separation with PSA or membrane systems show the opportunity to lower the energy penalty compared to single stand-alone units. The cryogenic unit uses differences in the boiling points of the flue gas components. CO₂ is transferred to the liquid phase, while other components are vented. The system as such has been proven in other industrial applications (like H₂ production). FEED studies on the implementation of this technology in cement plants are ongoing. However, as of yet, they have not reached a TRL higher than 6.

CO₂ capture using solid sorbents: Calcium-Looping

The so-called calcium looping (CaL; also known as carbonate looping) uses calcium oxide-based sorbents (limestone or cement raw meal) to capture carbon dioxide from the flue gases of a cement kiln. The process is based on the equilibrium of calcium carbonate (CaCO₃) to calcium oxide (CaO) and carbon dioxide (CO₂) at different temperatures and pressures ($CaCO_3 \leftrightarrow CaO + CO_2$). In a so-called carbonator, calcium oxide is put in contact with flue gases from the rotary kiln (integrated configuration) or from the cement plant (tail-end configuration) containing carbon dioxide to produce calcium carbonate ($CaO + CO_2 \rightarrow CaCO_3$). The exothermic carbonation reaction takes place at temperatures around 600 to 700 °C. The produced calcium carbonate is then directed to an oxyfuel-calciner for regeneration of the sorbent in an endothermic reaction (calcination) at temperatures above 900 °C ($CaCO_3 \rightarrow CaO + CO_2$), where the CO₂ is released in a concentrated gas stream (> 95 Vol.%). The produced CO₂ stream can be supplied for subsequent storage or utilisation after a final purification and compression step. The regenerated sorbent is partially transferred back to the carbonator, closing the loop. Additional fuel and oxygen are required for the regeneration of the sorbent. Oxygen can be supplied by an Air Separation Unit (ASU). Additional power is required for the ASU, the core CaL process and for the CO₂ purification (CPU). However, power can also be generated by a steam Rankine cycle (TP No. 9) utilising excess heat from the process. Under certain operation conditions the tail-end configuration of the CaL system might even become a net producer of electricity by exceeding its own demand.

Cement plants equipped with tail-end CaL configuration are characterised by two calcination reactors (plant's calciner and CaL's oxyfuel-calciner), which leads to a significant increase of thermal energy demand. In this configuration, the oxyfuel-calciner and the carbonator are circulating fluidised bed reactors (CFB). To assure a good fluidisation in the reactors, the limestone used as a sorbent is characterised by coarser particle sizes compared to the average particle size needed for the clinker burning process (100 to 300 µm and 10 to 20 µm, respectively). Due to the decay of the calcium oxide reactivity, the CaO-rich purge has to be removed from the oxyfuel-calciner and ground before being fed to the clinker burning process, replacing part of the limestone in the raw mix.

Taiwan Cement and Industrial Technology Research Institute (ITRI) started a calcium looping pilot project in 2013 in which a capture rate over 1 t CO₂/h was achieved.

A more recent variant for cement plants is the CaL integrated configuration, making use of entrained flow reactors. In this configuration the calciner of the plant and of the CaL process is the same, which leads to lower thermal energy demand compared to the tail-end configuration. In the integrated configuration a portion of the calcined raw meal produced in the oxy-fuel calciner is fed directly into the rotary kiln and the remaining material is directed to the carbonator, closing the cycle. A grinding step to correct the CaO-stream particle size coming from the oxyfuel-calciner is therefore unnecessary. In the EU-funded research project CLEANKER, the CaL integrated configuration with entrained flow reactors is presently being tested in a cement plant in Vernasca, Italy, at TRL7.

Indirect calcination for carbon capture

Indirect calcination technology addresses exclusively the capture of CO₂ process emissions. Thus, the overall CO₂ capture rate is limited to around 60% of the plant's total direct CO₂ emissions (for this share, the capture rate can reach up to 95%). It can be combined with other capture technologies like e.g. chemical absorption, physical adsorption or Oxyfuel technology in order to also capture CO₂ from fuel combustion and thus increase the overall capture rate. Indirect calcination technology involves an indirectly heated calciner, which enables the separation of the combustion gas stream from the relatively pure CO₂ stream generated in the limestone calcination process. An indirectly heated calciner replaces the conventional calciner of a kiln plant. The tube reactor is made of a special steel, which is heated from the outside, while the raw material flows in the inside. Despite the already high CO₂ concentration of the calcination gas stream (> 95 vol.% CO₂), the CO₂ still can be further purified to comply with any quality specifications set by downstream process chains, transport and storage or reuse.

A pilot plant based on a design by the Australian company Calix Ltd. was operated within the LEILAC EU research project in the cement plant in Lixhe, Belgium, which processed about 8-10 t/h material (approx. 70% of the reactor's design capacity). During the trial runs in 2019 and 2020, the calcination of cement raw meal as well as limestone was successfully proven. Technical risks such as the agglomeration of fine particles limiting the calcination rate, material build-ups, material transport from and to the host plant, and tube stability were addressed. The scale-up of this reactor is limited by the tube diameter, as the efficiency is subject to the heat transfer to the central tube. Therefore, the possibility to operate several parallel arranged tubes within a combustion chamber is currently being investigated in the LEILAC 2 project. In 2024 a reactor with four tubes in one combustion chamber (for 20% of total kiln feed) will be commissioned in a cement plant in Hannover, Germany to increase the TRL to 8 and prove long-term stability.

Post-combustion capture using mineral carbonation

Mineral carbonation is a chemical process in which magnesium and calcium silicates (e.g. serpentine, olivine, wollastonite) are reacted with CO₂ to form stable carbonates. A principle distinction is made between the so-called in-situ and ex-situ carbonation. In the in-situ process the CO₂ is injected into certain geological formations and the carbonation takes place underground, whereas in the ex-situ process the carbonation takes place above ground in a chemical processing plant.

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) can also be used as starting materials instead of natural minerals. An advantage of this capture process is the fact that it does not require the use of pure CO₂ for the mineral carbonation. The final output is inert carbonates, which can be used e.g. as construction materials or can be stored for long periods without risk of CO₂ leakage. As a result of this, mineral carbonation includes both the capture of CO₂ 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 with or without (mechanical or thermal) pretreatments. 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 occurring processes which are called “weathering”.

In contrast to this, 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. Indirect carbonation can be divided into different steps:

1. Separating of the metal from the mineral mix , e.g. in the presence of HCl or a molten salt
2. A series of hydration reactions to obtain the metal hydroxide
3. Carbonation reaction (carried out at elevated temperature and pressure)

A disadvantage of the process are the slow reaction rates of carbonation. However, there are different possibilities to enhance the reduction rate, e.g. elevated heat and pressures, chemical processing and mechanical treatment (grinding).

The results obtained with mineral carbonation show that industrial wastes are more reactive, so that the chemical reactions can be carried out under mild conditions.

Mineral carbonation technology is still in the R&D phase and up to now no industrial- scale adsorption units are known for CO₂ capture from flue gases. The required mineral mass to bind 1 t of CO₂ is between 1.8 and 3 t for relatively pure minerals. According to this, huge mining activities would be required to capture the CO₂ from cement plants. The potential for CO₂ carbonation of alkaline materials (not including natural recarbonation i.e. the CO₂ absorption by concrete) is estimated at 0.8 to 1.3 Gt CO₂/y in 2050. However, the potential is limited by effective conversion reactions, available access to appropriate initial materials and the availability of a market for the products.

4.48.4 Impact on energy consumption and consumables

All applications of carbon capture technologies involve the supply of thermal and/or electrical energy for the separation, purification and compression/liquefaction of CO₂. In the case of integrated calcium looping higher demand of thermal energy can result in an excess of electrical energy due to the high potential of waste heat recovery.

Table: Additional energy required to operate the capturing process

Technology	Thermal energy demand		Electrical energy demand	
		MJ/t cli		kWh/t cli
Oxyfuel technology	increase of up to 450	MJ/t cli	increase of 200 to 250	kWh/t cli
Absorption process – Monoethanolamine (MEA)	increase up to 3,500	MJ/t cli	increase of 80 to 129	kWh/t cli
Membranes	not applicable	MJ/t cli	increase of up to 300 to 400	kWh/t cli
Cryogenic capture combined with pressure swing adsorption	increase of 50 to 60	MJ/t cli	increase of 280 to 400	kWh/t cli
Temperature swing adsorption	increase of 2,000 to 4,000	MJ/t cli	increase of 100 to 110	kWh/t cli
Ca-Looping, tail-end (CFD reactors)	increase of 4,100 to 5,700	MJ/t cli	decrease of 70 to 240	kWh/t cli
Ca-Looping, integrated (entrained flow reactors)	increase of up to 2,450	MJ/t cli	increase of up to 50	kWh/t cli
Indirect calcination	increase of 100 to 305	MJ/t cli	increase of 60 to 100	kWh/t cli
Mineral carbonation	increase of 2,550	MJ/t cli	increase; exact figures n.a.	kWh/t cli

Some technologies require the additional raw materials or consumables, some of them can be produced onsite or must be bought from external sources.

Table: Additional raw materials or consumables

Technology	Material type	Amount	Unit
Oxyfuel technology	Oxygen	0.28 to 0.35	t/t cli
Absorption process – Monoethanolamine (MEA)	Replacement of absorbent	~ 0.001	t/t cli
	Steam import	0.6 to 0.8	MWh/t cli
Membranes	Replacement of membranes	n.a.	
Cryogenic capture combined with pressure swing adsorption	Replacement of sorbent	n.a.	
Temperature swing adsorption	Steam import	0.55 to 1.1	MWh/t cli
Ca-Looping, tail-end (CFD reactors)	Limestone (substitution of purged stream)	< 0.7	t/t cli
	Oxygen	0.45 to 0.5	t/tcli
Ca-Looping, integrated (entrained flow reactors)	Limestone (substitution of purged stream)	< 0.7	t/t cli
	Oxygen	up to 0.4	t/t cli
Indirect calcination	Replacement of reactor tubes	n.a.	
Mineral carbonation	Ca or Mg silicates	1.5 to 2.5 or more	t/t cli

4.48.5 CO₂ emission reduction potential

The direct CO₂ emission reduction potential is defined as the difference of the reference fossil CO₂ emissions (832 kg fossil CO₂ /t clinker) and the remaining fossil CO₂ emissions of the technology scenario. The remaining CO₂ emissions also comprise fossil CO₂ which might be generated to meet additional energy demand in the capture process and the applicable capture rate, which depends on the capture technology.

The CO₂ reduction potential can be further increased when fossil fuels are substituted by alternative ones containing biomass. The overall reduction potential can under these conditions even result in negative CO₂ emissions.

Table: CO₂ reduction potential

Technology	Direct CO ₂ emission reduction potential		Indirect CO ₂ emission reduction potential	
		kg CO ₂ /t cli		kg CO ₂ /t cli
Oxyfuel technology	decrease of 790	kg CO ₂ /t cli	increase of 110 to 140	kg CO ₂ /t cli
Absorption process – Monoethanolamine (MEA)	decrease of up to 775	kg CO ₂ /t cli	increase of up to 73	kg CO ₂ /t cli
Membranes	decrease of 670	kg CO ₂ /t cli	increase of 170 to 225	kg CO ₂ /t cli
Cryogenic capture combined with pressure swing adsorption	decrease of 750 to 790	kg CO ₂ /t cli	increase of 150 to 225	kg CO ₂ /t cli
Temperature swing adsorption	decrease of 710 to 730	kg CO ₂ /t cli	increase of 56 to 62	kg CO ₂ /t cli
Ca-Looping, tail-end (CFD reactors)	decrease of 710 to 760	kg CO ₂ /t cli	decrease of 40 to 130	kg CO ₂ /t cli
Ca-Looping, integrated (entrained flow reactors)	decrease of up to 780	kg CO ₂ /t cli	increase of up to 30	kg CO ₂ /t cli
Indirect calcination	decrease of 480 to 500	kg CO ₂ /t cli	increase of 28 to 45	kg CO ₂ /t cli
Mineral carbonation	decrease of 730 to 750	kg CO ₂ /t cli	n.a.	kg CO ₂ /t cli

Captured CO₂ refers to the total amount of processed CO₂ exported from the capture plant. The amount of CO₂ captured also comprises CO₂ originating directly from additional fuel use on site to operate the capture process. Captured CO₂ also includes biogenic CO₂ emissions as they result from the use of biomass such as being part of alternative fuels.

Table: Captured CO₂ (exported fossil and biogenic CO₂)

Technology	Exported fossil and biogenic CO ₂		Capture rate	
Oxyfuel technology	800 to 840	kg CO ₂ /t cli	90 - 95	%
Absorption process – Monoethanolamine (MEA)	up to 1100	kg CO ₂ /t cli	up to 95	%
Membranes	670	kg CO ₂ /t cli	up to 80	%
Cryogenic capture combined with pressure swing adsorption	760 to 800	kg CO ₂ /t cli	up to 95	%
Temperature swing adsorption	920 to 1080	kg CO ₂ /t cli	up to 90	%
Ca-Looping, tail-end (CFD reactors)	1130 to 1230	kg CO ₂ /t cli	up to 95	%
Ca-Looping, integrated (entrained flow reactors)	up to 1000	kg CO ₂ /t cli	up to 95	%
Indirect calcination	500	kg CO ₂ /t cli	up to 60	%
Mineral carbonation	750 to 960	kg CO ₂ /t cli	up to 90	%

The CO₂ reduction potential and energy consumption are influenced by different factors arising from site-specific conditions and minor variations in technology specifications.

Table: Main influencing parameters

Technology	Main influencing parameter on CO ₂ reduction potential and energy consumption
Oxyfuel technology	<ul style="list-style-type: none"> - Additional abatement of impurities at transition point to CO₂ processing unit to meet requirements from downstream processes - Level of false air (improvement of sealings requires attention) - Separation ratio of the CO₂ purification - Energy consumption of the CO₂ processing unit and oxygen supply system - Oxidizer purity (influences energy demand) - Design of implementation (with or without flue gas recirculation, full or partial application)
Absorption process – Monoethanolamine (MEA)	<ul style="list-style-type: none"> - Type of absorption process. Amine scrubbing processes require steam for generation, whereas the SkyMine process requires a huge amount of (renewable) power for the chlorine-alkali electrolysis - Steam generation on-site or steam import - The minimum CO₂ emission reduction potential is related to the partial capture based on the use of waste heat to match energy demand for regeneration resulting in a 50% capture rate - Available heat, low pressure steam, shaft work (supplied from co-located power plant) - Sour gas loading (SO₂, NO₂)
Membranes	<ul style="list-style-type: none"> - Operating conditions - Membrane's properties, selectivity and separation performance - For economical reasons the capture rate is limited to 80% - Technologies for further purification, processing and transport of the captured carbon dioxide are not considered
Cryogenic capture combined with pressure swing adsorption	<ul style="list-style-type: none"> - Type of process, sorbent and reactor influences the energy demand - Removal of impurities necessary to meet requirements from downstream processes
Temperature swing adsorption	<ul style="list-style-type: none"> - Type of process, sorbent and reactor influences the energy demand

Technology	Main influencing parameter on CO ₂ reduction potential and energy consumption
Ca-Looping, tail-end and integrated	<ul style="list-style-type: none"> - Type of sorbent - Degree of integration (amount of CaO-rich purge stream utilised as raw material in the cement plant) - CO₂ target purity - Type of fuel - Air tightness of the oxyfuel-calciner and downstream equipment
Indirect calcination	<ul style="list-style-type: none"> - Based on the requirements for CO₂ purity, especially with regard to impurities, an additional purification step might become necessary, which would influence the investment and operational costs - A CO₂ capture rate of about 60% (95% of CO₂ from calcination) is assumed. Higher capture rates are possible and would additionally require the capturing of the CO₂ emissions from the main burner or the decarbonation of fuels and electricity.
Mineral carbonation	<ul style="list-style-type: none"> - Type of process (direct /indirect carbonation) - Type of feedstock - Pretreatment of the minerals - Capture rate depends on process conditions such as exposure time, pressure and temperature - According to the literature, the requirement of thermal energy is around 3 GJ/t CO₂, which corresponds to 2.55 GJ/t cli. Additional electrical energy is needed for crushing and grinding processes and for gas compression

4.48.6 Technical Readiness

The Technology Readiness Level (TRL) is assessed for application of the respective technology in cement plants at scale. Some technologies might have a higher TRL in other sectors but there is limited experience of their transferability from those applications in other industries to the cement production process.

Table: Technology Readiness Levels (TRL) for application in the cement sector

Technology	TRL 2022	Applicability for industry at TRL >8 expected around
Oxyfuel technology	6	2025
Absorption process – Monoethanolamine (MEA)	8 – 9	2022
Membranes	4 – 5	2030 - 2040
Cryogenic capture combined with pressure swing adsorption	5 – 6	2030
Temperature swing adsorption	6 – 7	2030
Ca-Looping, tail-end (CFD reactors)	7 – 8	2025
Ca-Looping, integrated (entrained flow reactors)	6 – 7	2030
Indirect calcination	6 – 7	2025
Mineral carbonation	5 – 6	2030

4.48.7 Investment figures and operational costs

As costs can vary due to different cement plant situations, the following cost estimation serves as comparison basis for the different capture technologies taking into account the assumptions given in section 4.48.2:

- Production capacity 6,000 t/d, which is expected to be the dominant kiln size in 2050 on a global scale.
- All investment figures and operational costs are referred to 2020 as the reference year. Since inflation is difficult to forecast and since it can be very different from region to region, no inflation has been taken into account. The approach chosen is in particular important for big investment projects such as carbon capture technology. As the projects will be completed many years in the future, the costs and investment figures shown are mainly to be used as a comparison between the different technologies.
- CAPEX figures for capture projects are given for the capture plant only. This allows for a better comparison between the capture technologies because site specific investments are excluded, such as onsite intermediate CO₂ storage, upgrade of power supply, demolishing old equipment, water treatment, CO₂ logistics on site, and finally transport or storage. These uncertainties in investment figures for site specific investments can require up to 100% additional investment as compared to the figures for the actual capture plant.
- While investment figures are a significant part of the overall expenditures the upcoming capture projects indicate that the total project costs can still be significantly higher.

Table: Oxyfuel technology - Investment figures and operational costs

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2020	200 to 250	21 to 24 increase	290 to 330	22 to 25 increase
2030	200 to 230	21 to 23 increase	260 to 290	23 to 26 increase
2050	200 to 230	18 to 21 increase	260 to 290	20 to 22 increase

Remarks:

- Costs calculation include both design configurations with and without recirculation
- Investment figures include oxygen supply and CO₂ purification and compression.

Table: Absorption process – Monoethanolamine (MEA) Investment figures and operational costs

	Investment [Mio €]	Operational [€/t cli]
2020	200 to 275	increase up to 49
2030	200 to 275	increase up to 50
2050	200 to 275	increase up to 48

Remarks:

- Steam import is included in the operational costs
- Basically, uncertainties regarding the cost estimation result due to the site-specific boundary conditions (additional emissions abatement), steam generation (onsite or import) and targeted capture rate

Table: Membranes - Investment figures and operational costs

	Investment [Mio €]	Operational [€/t cli]
2020	not available	not available
2030	190 to 260	increase 30 to 40
2050	190 to 260	increase 25 to 33

Remarks:

- Membrane technologies are in an early development status so that reliable cost estimations are not available
- The investment costs are based on a case study by Roussanaly
- The price for the replacement of membranes is not included in the operational costs
- 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 CO₂ capture with membrane technologies could range between 43 €/t cli and 63 €/t cli (depending on fuel and electricity prices) which corresponds to former data in the technical literature. Membranes still show significant potential for improvement. Based on this, lower costs of less than 25 €/t CO₂ avoided are predicted for 2030 and 2050

Table: Cryogenic capture combined with pressure swing adsorption
Investment figures and operational costs

	Investment [Mio €]	Operational [€/t cli]
2020	not applicable	not applicable
2030	180 to 230	increase of 29 to 42
2050	180 to 230	increase of 24 to 34

Remarks:

- The capture process is based on the combination of PSA and cryogenic separation.

Table: Temperature swing adsorption - Investment figures and operational costs

	Investment [Mio €]	Operational [€/t cli]
2020	not applicable	not applicable
2030	180 to 235	increase of 38 to 58
2050	180 to 235	increase of 36 to 56

Remarks:

- The capture process is based on the combination of PSA and cryogenic separation.

Table: Ca-Looping tail-end configuration (CFB reactors)
Investment figures and operational costs

	Investment [Mio €]	Operational [€/t cli]
2020	365 to 495	up to 11 increase
2030	330 to 450	up to 11 increase
2050	330 to 450	5 to 12

Remarks:

- Different excess heat streams and heat to be rejected from the carbonator is used for power generation. In this way not only the power demand of the cement and capture plant can be covered, but excess power can also be sold. This implies the availability of power infrastructure and the permission to supply the power to the grid.

Table: Ca-Looping integrated configuration (Entrained flow reactors)
Investment figures and operational costs

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2020	330 to 475	up to 16 increase	380 to 540	up to 16 increase
2030	300 to 425	up to 16 increase	345 to 490	up to 16 increase
2050	300 to 425	up to 15 increase	345 to 490	up to 15 increase

Remarks:

- Different excess heat streams and heat to be rejected from the carbonator are used for power generation. In this way the power demand of the cement and capture plant can be partly covered.

Table: Indirect calcination - Investment figures and operational costs

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2020	220 to 290	5 to 9 increase	200 to 260	6 to 9 increase
2030	220 to 290	6 to 10 increase	200 to 260	6 to 10 increase
2050	220 to 290	5 to 8 increase	200 to 260	5 to 8 increase

Remarks:

- Costs for a CO₂ purification unit are included to match the CO₂ purity requirements from downstream processes.
- Costs are based on capture rate of 60%.
- The scale-up of indirect heating technology for kilns of 2 million t/a is theoretically feasible, but currently there are no studies that support the application of this technology in such kilns. The number of parallel arranged tubes required and their integration in a 2 million t/a kiln still needs to be investigated
- Effects of electrical indirect heating on power consumption are excluded.
- Replacement of tubes after a certain time of operation becomes necessary and is excluded in the the above estimation

Table: Mineral carbonation - Investment figures and operational costs

	Investment [Mio €]	Operational [€/t cli]
2020	not available	not available
2030	not available	not available
2050	not available	not available

Remarks:

- Cost estimations for the mineral carbonation process have been published in the technical literature. According to this, the total cost of in-situ mineral carbonation could range from 65 to 117 €/t CO₂
- For ex-situ mineral carbonation, the cost estimations range from 45 and 190 \$/t CO₂, depending on the type of feedstock

4.48.8 Conditions, barriers, constraints, enabling framework

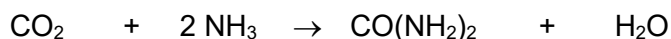
The net zero transition of the cement sector requires a framework which includes political financial, social and technical aspects. Among the many technical ones arising from the different technologies described, the following are worth being highlighted:

- Most technologies are still not proven at demo-scale in the cement industry. In particular, technologies with low TRL require the proof of scale-up to full-size implementation.
- Thermal and/or electrical energy consumption will increase.
- All CO₂ captured requires a respective infrastructure for transport and access to storage sites or reuse options.
- Solvents and sorbents might be very costly. They can degrade and degradation products must be examined.
- Solvents/sorbents/membranes need to be improved with regard to separation efficiency, sensitivity towards impurities and temperature resistance
- Appropriate regulation and economic incentives concerning the capture of biogenic CO₂ (negative emissions)
- Using solid sorbents as in Ca-Looping or mineral carbonation processes, a high effort for material handling is necessary (large material transport and storage requirements, high energy demand for the mining, transportation and preparation of the mineral)
- Limiting factor: Availability of materials like solvents, minerals, alkalinity etc. Negative emissions can be achieved capturing biogenic CO₂ (linked to the use of alternative fuels containing biomass) and subsequent storage or utilisation.

4.49 Technology Paper No. 49: CO₂ use: Basic chemicals, urea, formic acid, polymers

The CO₂ captured from the flue gases of industrial emitters can be used as a starting material for the synthesis of chemicals or special polymers. In principle, there are many ways to synthesise organic molecules from CO₂. However, the use of CO₂ for chemical syntheses requires efficient catalytic systems in most cases. In this context, the hydrogenation of CO₂ is an important possibility for the chemical conversion of CO₂.

Urea (CO(NH₂)₂) is the main product for which CO₂ is used as a C1 building block. It is produced from CO₂ and NH₃ under high pressure and temperature:



In most cases, the urea production is carried out in the vicinity of ammonia plants as large amounts of CO₂ are generated in the syngas production for the ammonia synthesis. Most of the produced urea is used as agricultural fertilizer.

Formic acid is another basic chemical which can be produced by a selective hydrogenation of CO₂:



Recent research projects, e.g. “Power-2-Formic Acid” by TNO (Netherlands Organisation for applied Scientific Research) or “CO₂PERATE” by Catalisti, aim to improve and prove the concept itself. While several other processes have already proven the technical feasibility, industry still lacks representative pilot plants and long-term studies on their operation. However, the key limiting factor for projects of this kind is the economic sustainability. Formic acid and its salts are used in different industrial applications, e.g. in the leather industry, as deicing agents or as preservatives.

In addition, and as an alternative carbon source, the captured CO₂ can be used to produce polymers such as polycarbonates and polyurethanes. For example, polycarbonates can be produced by a reaction between CO₂ and epoxides. Polyols, which are a starting material for polyurethane production, can also use CO₂ captured from flue gas streams. A first industrial-scale production line has gone online in Germany in 2017. Among others, this process has been developed within the Carbon2Chem project between 2016 and 2020 and will be continued until 2024.

To meet the required global CO₂ reduction targets for climate protection, the relevant amounts of CO₂ have to be stored or reused. It is evident that the potential for the production of certain chemicals and polymers from captured CO₂ is limited – taking into account the current world market for the respective products. However, the motivation of chemical companies for the reuse of captured CO₂ as future carbon feedstock is to achieve sustainable production and to broaden their raw material basis.

Impact on energy consumption

thermal:	not applicable	MJ/t cli	electric:	not applicable	kWh/t cli
----------	----------------	----------	-----------	----------------	-----------

The further utilisation of captured CO₂ for the production of basic chemicals does not affect the energy consumption of the actual clinker burning process.

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cli	indirect:	not applicable	kg CO ₂ /t cli
---------	----------------	---------------------------	-----------	----------------	---------------------------

Material input

Hydrogen (most processes)	Type of material	not available	t/t cli
---------------------------	------------------	---------------	---------

Technical Readiness

TRL 2022: 6-9 (9 for formic acid)

The main influencing parameters are

- Purity of the CO₂ gas stream
- Added value related to aspired product
- Availability of carbon neutral power and green hydrogen

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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 CO₂ for the production of basic chemicals is still in an early status of development. Reliable data about the costs for industrial scale application are not yet available.

Conditions, barriers, constraints, enabling framework

- Limited markets for CO₂-based products
- Competition with traditional production routes
- Pricing in carbon footprint would accelerate market entry
- Most pathways depend on a significant input of H₂ gas and thus the availability of carbon neutral power

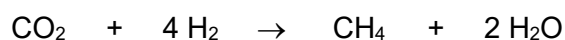
4.50 Technology Paper No. 50: CO₂ use: Power-to-gas (CH₄)

The use of captured CO₂ for methane (CH₄) production is one of the most important technologies for storage concepts for electrical energy. The hydrogen needed for its production must be generated with electrical energy from carbon neutral or renewable sources. The methane produced could then be stored in the existing natural gas grids, which offer a comparably large storage capacity.

A power-to-gas project consists of the following main process steps:

- the capture of CO₂ from flue gases of power plants, cement kilns or other industrial sources
- the production of hydrogen by water electrolysis using carbon-neutral electrical energy
- the catalytic conversion of CO₂ with hydrogen to form methane

The captured CO₂ gas stream should exhibit a sufficient purity for the subsequent catalytic reactions. Possible technologies for the hydrogen production are alkaline electrolysis, polymer electrolyte membrane (PEM) electrolysis and solid oxide electrolysis (SOEC). All of the above-mentioned electrolysis processes require a respective amount of electrical energy for hydrogen production. Methane is produced with the so-called Sabatier reaction, an exothermic catalytic reaction between CO₂ and hydrogen in the presence of transition metal catalysts (mostly Ni catalysts):



The main demand for electrical energy is needed for the hydrogen production and therefore not relevant in this paper.

Pilot trials are being carried out in different countries, utilising CO₂ from different sources. However, there is no operational experience from industrial-scale projects, neither in the cement industry nor in the power sector. Up to now, the economical feasibility is not given, as natural gas prices are significantly lower than the prices of CH₄ from catalytic methanation. Additional hurdles for this process are, on one hand, the supply of H₂ gas produced with carbon-neutral energy and, on the other hand, the price for the green hydrogen production.

Impact on energy consumption

thermal:	not applicable	MJ/t cli	electric:	177 to 186*	kWh/t cli
----------	----------------	----------	-----------	-------------	-----------

*Energy consumption for the conversion of CO₂ to CH₄, no influence on or part of clinker production

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cli	indirect:	16 to 20*	kg CO ₂ /t cli
---------	----------------	---------------------------	-----------	-----------	---------------------------

*CO₂ from electric power production with carbon footprint according to Annex II

Material input

Hydrogen for CO ₂ reduction	0,15*	t/t cli
--	-------	---------

*Not used within the clinker production process

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Costs for electrical energy from carbon neutral sources
- Taxes and duties on the electrical energy
- Purity of the CO₂ gas stream; H₂ gas supply

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2020	26	510	26	510
2030	18	353	18	353
2050	13	234	13	234

Remarks:

- The costs for the installation of a power-to-gas plant are the same – both for the installation in an existing cement plant and in a new cement plant
- Calculations on investment and operational costs as well as material input were performed with 100% of the emitted CO₂ from clinker production (1.4 million t CO₂ /a)
- Investment costs were focused on the methanation plant while no capture system or electrolyser was considered
- While the operation of a P2G plant is possible with all kinds of H₂-gas, the only expedient option is if it is generated with carbon neutral power. Therefore, in the cost estimation the assumed price refers to carbon-neutral H₂
- Operating costs include electricity for the methanation and H₂ demand and do not cover costs for labour, insurance, cooling water, catalyst replacement etc.
- Due to a lack of feasibility studies for PtG projects the given calculations were made based on literature and most probable scenarios
- The cost estimations do not include the revenues from selling the product

Conditions, barriers, constraints, enabling framework

- Availability of carbon neutral power and green hydrogen
- Electricity prices
- Natural gas prices
- No incentives for the production of carbon neutral methane
- Legal framework for carbon capture and use

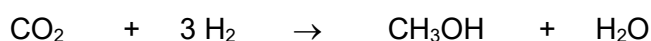
4.51 Technology Paper No. 51: CO₂ use: Power-to-liquids (Methanol)

A potential reuse technology named the power-to-liquids (P2L) process, is the conversion of electrical energy from carbon-neutral sources with CO₂ into fuels or methanol.

A power-to-liquids project consists of the following main process steps:

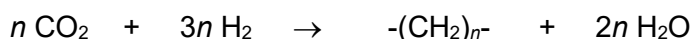
- The capture of CO₂ from the flue gases of power plants or other industrial sources
- The production of hydrogen by water electrolysis using carbon neutral electrical energy
- The catalytic conversion of CO₂ with hydrogen to form CO (carbon monoxide) (RWGS – Reverse Water Gas Shift) for further conversion to methanol or fuels using additional hydrogen

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



The captured CO₂ 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 CO₂ captured from a nearby geothermal power plant to produce a CO₂-rich syngas. Worldwide, several plants between 1,000 t/a and 200,000 t/a have already been in operation for several years or will be operated in the coming years. The methanol produced is a basic chemical compound which can be used for a variety of chemical conversions to other products, or can also be used as a fuel. For example, in some countries, gasoline is blended with small percentages of methanol. With projects like the HYNØVI (500 kt CO₂ /a converted to methanol), Westküste 100 (up to 777 kt CO₂ /a converted to hydro-carbons) and the finished European HORIZON2020 Project “MefCO2”, big capacities will soon be operational. Similar to the power-to-gas concept, the power-to-liquids concept is therefore also an interesting option for energy storage.

Another option for the power-to-liquids concept is the catalytic conversion of CO₂ with renewable hydrogen to fuels:



A German start-up company has built a demonstration plant which can produce up to one barrel of fuels per day (petrol, diesel, kerosene). However, the economical feasibility is not yet given. Nevertheless, several other projects (Rethinking Fuels” by the Ministry of Transport Baden Wurttemberg) and companies e.g., “Twelve” (USA) or Nordic Electrofuel (Norway) are aiming to improve and establish existing processes.

Impact on energy consumption

thermal:	not applicable	MJ/t cli	electric:	-91 to 94*	kWh/t cli
----------	----------------	----------	-----------	------------	-----------

*Energy consumption for the conversion of CO₂ to Methanol, no influence on or part of clinker production

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cli	indirect:	29 to 54*	kg CO ₂ /t cli
---------	----------------	---------------------------	-----------	-----------	---------------------------

*CO₂ from electric power production with carbon footprint according to Annex II

Material input

Hydrogen for MeOH production	0.1*	t/t cli
------------------------------	------	---------

*Not used within the clinker production process

Technical Readiness

TRL 2022: 8 (low-temp; ASTM approval) applicability for industry at TRL >8 expected about: 2025

The main influencing parameters are

- Costs for electrical energy from carbon-neutral sources
- Costs for hydrogen production from carbon-neutral sources
- Taxes and duties on the electrical energy

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cli]	Investment [Mio €]	Operational [€/t cli]
2020	188 to 196	347	188 to 196	347
2030	185 to 194	239	185 to 194	239
2050	178 to 186	158	178 to 186	158

Remarks:

- The costs for the installation of a power-to-liquids plant are the same – both for the installation in an existing cement plant or in a new cement plant
- Calculations on investment and operational costs as well as material input were performed with 100% of the emitted CO₂ from clinker production (1.4 Mio t CO₂/a)
- Investment costs cover the CO₂ conversion including CO synthesis (RWGS), while no capture system or electrolyser was considered
- While operation of a P2L plant is possible with all kinds of H₂-gas, the only expedient option is if it is generated with carbon-neutral power. Therefore, in the operational cost estimation an assumed price of green H₂-gas is used
- Operational costs only include electricity and H₂ demand and do not cover costs for labour, insurance, cooling water, catalyst replacement etc.
- Operational costs are strongly dependent on the costs for hydrogen
- Investment costs will significantly decrease over the decades due to the development of the manufacturing process (today specialised manufacturing, in future automated)
- The cost estimations do not include the revenues from selling the product
- Due to a lack of feasibility studies for PtL projects the given calculations were made based on literature and most probable scenarios

Conditions, barriers, constraints, enabling framework

- Availability of carbon-neutral power and green hydrogen
- Competitive market with methanol or fuels from traditional production processes
- No incentives for the production of renewable methanol or fuels

4.52 Technology Paper No. 52: CO₂ use: Enhanced Oil or Gas Recovery (EOR/EGR)

Enhanced oil or gas recovery (EOR/EGR) is the general term for various techniques which can be applied to increase the recovery of oil and gas in depleted or high-viscosity oil or gas fields. One of those possibilities is to inject CO₂ into these fields to boost the oil or gas production. By this method, CO₂ injection has the potential not only to increase the yield of an oil or gas field, but also to store the injected CO₂ for example from carbon capture projects. In contrast to other utilisation routes for CO₂, there is already a market for CO₂ in EOR/EGR and revenue can be achieved for the supply of CO₂ to oil and gas producers.

Globally, this technology has been predominantly applied in oil production up to now. Around 5 to 40% of the oil in a reservoir can be produced with the so-called primary production (natural reservoir drives are used to recover the oil) and an additional 10 to 20% with the secondary production, which would include water flooding of the reservoir. 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 would be inaccessible (immobile oil).

EOR technologies include the injection of different agents into the reservoir to extract immobile reserves of oil. CO₂ can be used, but also steam, chemicals or polymers. In the case of CO₂, most of the injected CO₂ 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 CO₂ has to be retained in underground storage. In this case, further 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 CO₂ for EOR projects has been provided from naturally-occurring underground reservoirs. However, today captured CO₂ 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 CO₂ from cement plants, while power plants (Boundary Dam Power Station (Canada), Petra Nova (United States) or Weyburn-Midale (Canada)) are already making use of this possibility.

Long-term experience has been available for more than 40 years from different projects, e.g. from the Weyburn Project (Saskatchewan/Canada), where 8,500 t/d have been injected into a depleted oil field. In this case, each tonne of injected CO₂ increased the oil production by 2 to 3 barrels.

The further utilisation of captured CO₂ for EOR does not affect the energy consumption of the clinker burning process. However, the energy demand of the applied capture technology has to be taken into account.

Impact on energy consumption

thermal:	not applicable	MJ/t cli	electric:	not applicable	kWh/t cli
----------	----------------	----------	-----------	----------------	-----------

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cli	indirect:	not applicable	kg CO ₂ /t cli
---------	----------------	---------------------------	-----------	----------------	---------------------------

Material input

not applicable	t/t cli
----------------	---------

Technical Readiness

TRL 2022: 9

The main influencing parameters are

- Pipeline specifications (CO₂ purity)
- Competitive market with CO₂ from natural sources

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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

Remarks:

- In the past, the CO₂ supply price was mainly dependent on the current oil price and varied between 10 and 30 US-\$/t CO₂ in the past 30 years. In the future, this price will develop with the need to store CO₂ from industrial sources on the one hand and on the availability of storage and infrastructure capacity on the other hand.

Conditions, barriers, constraints, enabling framework

- Various local requirements, e.g. oil or gas reservoirs, CO₂ sources, transport infrastructure etc.

4.53 Technology Paper No. 53: CO₂ use: Algae capture and fuel production, biofuels

The mitigation of CO₂ by algae, which absorb CO₂ and convert it via photosynthesis to biomass is an option to produce biofuels or fish and animal feed. CO₂ 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 brackish seawater or wastewater. They grow through photosynthesis and their development requires light, CO₂, water and some mineral salts. In principal, microalgae differ in shape, size, chemical structure, composition and colour, and can be classified in different categories. Such 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 algae can be harvested, dried and used as a renewable fuel to replace fossil fuels 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 electrical energy for all process steps is sourced from carbon neutral ones, otherwise the process would be associated with additional CO₂ emissions. The space requirement for an algae project is high: a 6,000 t/d cement kiln with an annual CO₂ output of 1.37 Mio. t would have space requirement for algae cultures of up to 140 km² (using Chlorella), 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 different kind of crops. 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 CO₂ capture have been carried out in the cement industry, e.g. in cement plants in Morocco, Sweden, Turkey, France, Canada, Brazil, Portugal, etc. The tests with real flue gas from 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 performed in a Taiwanese cement plant with a 20 hectare production. Through this, the CO₂ emissions of the cement plant could be reduced by 4,800 t/yr.

Impact on energy consumption

thermal:	increase; exact figures not available	MJ/t cli	electric:	increase; exact figures not available	kWh/t cli
----------	---------------------------------------	----------	-----------	---------------------------------------	-----------

Remark:

- The required electricity for algae cultivation has to be sourced from carbon neutral energies.

CO₂ emission reduction

direct:	decrease up to 750	kg CO ₂ /t cli	indirect:	not applicable	kg CO ₂ /t cli
---------	--------------------	---------------------------	-----------	----------------	---------------------------

Remark:

- max. 90% capture is assumed, but space requirement may prevent this.

Material input

water, nutrients	exact figures not available	t/t cli
------------------	-----------------------------	---------

Technical Readiness

TRL 2022: 7

applicability for industry at TRL >8 expected about: 2030

The main influencing parameters are

- Composition of the flue gas, trace components (e.g. SO_x, NO_x)
- Temperature, pH value, type of nutrients
- Algae physiology

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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:

- Investment costs are not yet predictable, since all existing projects are still on a R&D level and the scaling up process ongoing.

Conditions, barriers, constraints, enabling framework

- Large land areas are required for algae cultivation
- Large quantities of nutrients are required
- Only operable with sufficient light

4.54 Technology Paper No. 54: Natural Carbonation

Carbonation is the formation of calcium carbonate from calcium-containing hydration products in the hardened cement paste of concrete. In this process, calcium silicate hydrate (CSH) and portlandite ($\text{Ca}(\text{OH})_2$) react with CO_2 from the air under alternating humidity conditions (in particular at relative humidity around 50%) to form calcium carbonate. The carbonation of $\text{Ca}(\text{OH})_2$ to CaCO_3 leads to a volume increase of about 11% and consequently to the densification (decrease of pore volume by up to about 25%) and the increase of the strengths of the hardened cement paste by up to 50%. The carbonation of the CSH phases is rather associated with a decrease in volume, so that hardened cement paste ultimately shrinks as a result of carbonation. Due to carbonation the pH value of the pore solution drops from about 13.5 to below 9. At pH values lower than 11.5 the passivation layer of the reinforcing steel is getting lost and the reinforcement may corrode. The rate of carbonation is low in normal concrete under ambient conditions (0.04% CO_2 in air) and usually only a few centimetres of the concrete cover are affected by carbonation during the service life of concrete.

In its report published in August 2021, the Intergovernmental Panel on Climate Change (IPCC) recognised and quantified the carbonation of cement-bound building materials as a "carbon sink" for the first time. The report refers to the paper from Xi et al. who estimated that carbonation of cementitious materials offset CO_2 emissions equivalent to an amount of 43% of CO_2 process emissions from cement production.

To quantify natural carbonation, Andersson et al. chose an approach according to which the CO_2 uptake of cement-bound building materials in a country or region is compared with the CO_2 emissions from cement production in the same period. Three different levels with varying degrees of accuracy are proposed.

- Tier 3 determines the annual CO_2 uptake of the existing building stock using extensive knowledge of the historical use of cement in its various applications
- Tier 2 has a lower accuracy and can be applied if data on cement and concrete use are only available for a few years. For cases where neither the data basis for calculations according to Tier 3 nor according to Tier 2 is available, a simplified procedure (Tier 1) is proposed
- In Tier 1, the annual CO_2 uptake of a country's cement-bound building materials in the use phase can be estimated at 20% of the CO_2 process emissions from calcination in the respective year. The annual CO_2 uptake at the end of life (i.e. during and after building demolition) in this Tier is 2% and that in secondary use is 1%. Overall, 23% of the annual CO_2 process emissions of cement production are thus bound by carbonation. The above percentages were determined via the evaluation of seven published studies that fulfil the requirements according to Tier 3 or Tier 2

While according to the CO_2 absorption of the entire building stock of a geographical region is estimated, for life cycle assessments, it is of interest how much CO_2 individual concrete components can absorb as a function of time. Annex BB of EN 16757 gives information that can be used to estimate the CO_2 absorption of cement-bound building elements. For the use phase of concrete elements, a detailed calculation method is provided which allows to estimate the progress of the carbonation front and the corresponding CO_2 uptake with time, based on the concrete strength, the exposure conditions and cement constituents or concrete additions used.

According to the standard, the CO₂ uptake in kg per m² concrete surface during t years can be calculated as

$$CO_2 \text{ uptake} = k * \left(\sqrt{t} / 1000 \right) * U_{tcc} * C * (D_c)$$

In this formula, U_{tcc} is the maximum theoretical uptake in kg CO₂/kg cement, For Portland cement (CEM I), the value of U_{tcc} is given as 0,49 kg CO₂/kg cement. C is the cement content in kg/m³ of concrete. k is a factor describing the carbonation rate [mm/year^{0,5}] and D_c the degree of carbonation [%]. For both k and D_c, values are provided in the standard.

With this formula, e.g. the CO₂ uptake of a civil engineering structure – (Concrete strength class C40/50, 400 kg CEM I per m³) with surfaces exposed to rain is calculated as 1,8 kg/m² over a service life of 100 years.

For concrete exposed to a dry indoor air climate and covered with paint or wall paper (strength class C25/30, 280 kg CEM I per m³), the CO₂ uptake is calculated as 2,5 kg/m² over a service life of 100 years.

Moreover, Annex BB of EN 16757 addresses the carbonation potential after the use phase: the CO₂ uptake during the „end of life“ (i.e. demolition, crushing and stockpiling) phase of concrete largely depends on the waste handling and the storage of the crushed concrete. Whether crushed concrete is landfilled or whether it is recycled and replaces primary material may also have a decisive influence on the carbonation potential. Estimates are provided in the standard on the potential carbonation during these life cycle stages.

Carbonatable calcium fractions from pozzolanas such as fly ash or from latent hydraulic materials such as ground granulated blast furnace slag in cement are neglected in [2] when determining the carbonation potential. As a conservative approach, only the reactive calcium of the Portland cement clinker is considered for carbonation.

4.55 Technology Paper No. 55: Enforced (re)carbonation/mineralisation

During its use, concrete reintegrates CO_2 in a natural and slow way to an amount which corresponds - in a conservative estimate - to approx. 20% of the CO_2 emitted from the limestone during clinker production. In this process, calcium silicate hydrate (CSH) phases and portlandite ($\text{Ca}(\text{OH})_2$) are carbonated. The rate of carbonation is low in normal concrete and because it is diffusion controlled it closely follows the square root of time function. Most concrete elements have a dense structure, so that even after many decades usually only a few centimetres of the concrete cover are affected by carbonation. A dense concrete cover therefore protects the reinforcing steel from corrosion and ensures durable reinforced concrete elements (see Technology Paper No. 54).

According to the assumptions mentioned above, about 80% of the hardened cement paste in concrete elements is not carbonated at the end of service life this either represents a potential CO_2 -free calcium source (see Technology Paper No. 20) or has the potential to reincorporate further CO_2 (the focus of this paper). In principle, CO_2 to an amount released during the calcination of the limestone in the production of clinker can be re-incorporated. In addition, there is a CO_2 binding potential of non-clinker-based CSH phases or unreacted carbonatable fractions of latent hydraulic or pozzolanic materials such as granulated blast furnace slag or fly ash. The finer the hardened cement paste, the faster it can uptake CO_2 under appropriate moisture conditions.

Currently, various processing methods for separating fine hardened cement paste and aggregates from waste concrete are being tested in the industry (e.g. electrodynamic fragmentation in combination with various crusher stages). In the case of stockpile storage of separated hardened cement paste, only the outer centimetres of the stockpile usually carbonate, so that the carbonation potential of the material should remain largely intact over a longer period of time. Through CO_2 - and moisture treatment - so-called enforced carbonation or mineralisation - further CO_2 can be incorporated into the hardened cement paste many times faster than by the slow, natural carbonation process. Technologies for enforced carbonation are being further developed (e.g. with CO_2 -saturated steam or flue gases) which enable very rapid carbonation of the hardened cement paste fraction. Depending on the grain size and porosity of the recycled hardened cement paste, moisture contents of around 5 to 10 mass % and temperatures between 40 to 60 °C usually ensure rapid carbonation, which can be further accelerated by pressure. Higher temperatures significantly reduce the solubility of $\text{Ca}(\text{OH})_2$ and thus the progress of carbonation. With appropriate moisture and CO_2 conditions, fine-ground cement paste can be carbonated to around 80% after around 15 minutes and almost completely after 2 hours. High carbonation rates can also be achieved with flue gas compositions that are common in cement plants (approx. 20% CO_2). After the carbonation of Portlandite, the calcium from the CSH phases reacts with CO_2 to form calcium carbonate and an amorphous aluminosilicate gel, which can have pozzolanic properties. Fine ground, carbonated cement paste can be used as a cement main constituent with properties at least comparable to limestone or even with pozzolanic properties.

The pozzolanic activity leads to a phase formation similar to composite cements containing fly ash and limestone and can improve the compressive strength of cement even at early ages (see Technology Paper No. 40).

In principle, industrial systems for the carbonation of crushed concrete or hardened cement paste and for concrete product treatment already exist such as e.g. curing chambers with

steam and/or CO₂. Nevertheless, enforced carbonation of crushed concrete or hardened cement paste is not yet being operated on an industrial scale. First pilot projects exist and some development work is necessary to adapt existing systems to enforced carbonation.

Enforced carbonation of hardened cement paste has the potential to be a promising CCU technology for the cement industry and could be an additional key element on the way to the circular economy of cement and concrete. On the one hand, CO₂ can be incorporated, and on the other hand, a material is produced that can be used as a (possibly pozzolanic) cement constituent to reduce the clinker factor (see Technology Paper No. 40).

Challenges are certainly the large quantities of material to be handled. For one tonne of (pure) hardened cement paste, theoretically about 5 t of crushed concrete have to be processed. The separation of crushed concrete during demolition and the separation of the hardened cement paste from the aggregate must be assured. For processing and appropriate interim storage, areas are needed as close as possible to the demolition site or the cement plant (transport). The CO₂ treatment process should be designed for a high throughput (high CO₂ uptake with the shortest possible retention times) similar to a cement kiln. For a direct use of flue gases from cement kilns for CO₂-treatment, the local proximity between the waste concrete processing and the cement plant would be of great advantage.

Compared to the existing recycling practice of concrete, new source streams must be initiated which take into account the complete reuse of materials used in crushed concrete for the production of new fresh concrete (recycled aggregates) as well as for clinker and cement production (recycled cement paste).

In addition to the complete carbonation or / mineralisation of hardened cement paste from crushed concrete, there are also approaches in which partial carbonation of hardened cement paste in fresh or young concrete is used to various degrees for strength improvement and CO₂ storage, which are briefly discussed below.

Use of CO₂ to mineralise CaCO₃ crystallites in fresh concrete

During mixing ca. 0,1 – 0,3 mass-% of CO₂ (related to cement weight) are injected into the fresh concrete. The CO₂ reacts with calcium ions in fresh concrete and forms calcium carbonate seeds, which can improve the further hydration process to a certain extent as a kind of admixture. The effective CO₂ incorporation for an average concrete with 300 kg of cement per cubic metre is between 0.3 and 0.9 kg of CO₂ per cubic metre.

Further CO₂ savings can be achieved indirectly by reducing the cement content in the concrete, taking advantage of the improved hydration through seeding. Typical cement reductions are approx. 5 mass-%.

Use of CO₂ to carbonise concrete elements

In this process, unreinforced precast elements or concrete products such as concrete masonry blocks or pavers, are treated with steam and CO₂ to increase the early strength and to incorporate CO₂. This is usually done after demoulding and after few hours of drying. Depending on the dimensions of the concrete element, the duration of the treatment (several hours) and the CO₂ concentration and pressure, CO₂ absorption of up to 35 mass-% in relation to the cement mass is reported. Enforced carbonation can lead to an increase in early strength of concrete. The further strength development results from ongoing hydration of the binder. There is little knowledge about the effects of such CO₂ treatments on further hydration or on the influences on durability aspects.

The natural carbonation potential is assumed to be widely exhausted by enforced carbonation. Further carbonation will only occur after crushing. This type of enforced carbonation is used in a few countries to a very limited extent, e.g. China, India.

More common in the production of unreinforced concrete elements such as pavers, is the use of CO₂ treatment chambers. Mostly only the upper millimetres of the concrete surface are carbonated quickly by means of a short CO₂ treatment in order to effectively reduce the efflorescence tendency of concrete products.

For all CO₂-treatment systems, the highly corrosive effect of the resulting carbonic acid on metal elements must be taken into account.

A special form of hardening via the carbonation of unhydrated calcium silicates (e.g. Wollastonite) is described in Technology Paper No. 44.

Impact on energy consumption

thermal:	not applicable	MJ/t cli <u>or</u> MJ/t cem	electric:	not applicable	kWh/t cli <u>or</u> kWh/t cem
----------	----------------	--------------------------------	-----------	----------------	----------------------------------

CO₂ emission reduction

direct:	not applicable	kg CO ₂ /t cli <u>or</u> kg CO ₂ /t cem	indirect:	not applicable	kg CO ₂ /t cli <u>or</u> kg CO ₂ /t cem
---------	----------------	--	-----------	----------------	--

Material input

not relevant	amount of material	t/t cli <u>or</u> t/t cem
--------------	--------------------	------------------------------

Technical Readiness

- Industrial systems for the processing of waste concrete (crushing, separating):
TRL 2022: 9 (Improvement in hardened cement paste separation necessary; target: complete separation of natural aggregates from hardened cement paste)
- Industrial systems for the enforced carbonation of waste concrete or hardened cement paste and for concrete product treatment
TRL 2022: 6
TRL 2030: 9

The main influencing parameters are

- Circular economy: selective demolition of concrete structures, collecting and processing of waste concrete, separation/recycling of aggregates on demolition site; transport of hardened concrete paste to CO₂ treatment & cement production (both in cement plant), natural carbonation during transport or storage reduces the effects of active carbonation (less pozzolanity)
- High transport costs if concrete has to be transported to the cement plant for crushing, separating and CO₂ treatment

Cost estimation

Cost estimation	New installation		Retrofit	
	Investment [Mio €]	Operational [€/t cem]	Investment [Mio €]	Operational [€/t cem]
2020	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, enabling framework

- Currently, crushed waste concrete from constructions is used for the production of cement and concrete only to some degree in a some regions; crushed concrete is instead mainly used for road substructures
- Processing (separation, crushing, fractionation etc.) of waste concrete must be improved in order to obtain recycled concrete fines; Source stream must be established
- Long transport distances from demolition site (processing) to CO₂ treatment and cement production
- Systems for enforced carbonation must be further developed, especially in the neighbourhood of existing cement plants for the use of flue gases (higher CO₂ uptake, lower retention time)
- Carbonation potential mainly depends on calcium-containing phases in cements, such as clinker, slag etc.
- Corresponding infrastructure for processing of waste concrete, an adequate quality assurance and transport systems must be established

5 Annex I: Key assumptions

Technical and financial calculations are based on the following key assumptions:

Cement plant:

One reference plant based on GCCA/GNR data, GNR-2019 world average:

Kiln type: Predominantly characterised as dry process

- 66% dry process with preheater and precalciner (PHPC)
- 20% dry process with preheater (PH) without precalciner
- 14% mixed kiln types (incl. 2% long dry, 2% semi-wet/semi-dry, 2% wet/shaft)

CO₂ emission reduction potential:

- Direct CO₂ emission changes (decreases and increases) refer to the original CO₂ intensity of the reference plant (832 kg fossil CO₂ /t clinker) resulting from the technology application in the production process of the cement plant.
- direct CO₂ emission reduction potential =
reference fossil CO₂ emissions – remaining fossil CO₂ emissions of technology scenario
- For the CO₂ capture technologies the remaining CO₂ emissions integrate CO₂ generated to meet additional energy demand in the capture process and the applicable capture rate, which is assumed at 95% in most scenarios.
- Indirect CO₂ emissions relate to changes in the use of electricity. This CO₂ is generated outwith the cement plant and its processes.
- Captured CO₂ refers to the total amount of processed CO₂ exported from the capture plant installed in or next to a cement plant. The amount captured integrates CO₂ originating from additional fuel use and biogenic CO₂ of alternative fuels. It excludes CO₂ vented as remaining flue gas.

Prices/costs:

- No inflation, 2020 cost basis
- Based on world averages and future estimates (fuel, electricity, investment, operational cost)
- Future price development of fuels and electricity based on IEA (World Energy Outlook 2021), ECRA industry expert interviews and MPP assessment, see also Annex II (performance data of reference plant)
- Indicated material inputs included in estimated operational cost
- For certain technologies, especially the use of alternative fuels, alternative raw materials and other main constituents, central European technology experience and conditions were taken as a basis
- No depreciation of investment considered in operational cost
- No CO₂ cost effect of emission trading or taxes, etc.
- No learning rates for existing, well-known technologies

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

Definition of reference plant (Global average data of GCCA Roadmap and GNR-2019 data used for ECRA Technology Papers 2022)

Parameter	Unit	Reference plant (state of the art plant) 2020 / 2030 / 2050
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	2.25 Mio.
clinker/cement factor	t cli/t cem, %	72.4
clinker/cement factor, reference in Technology Papers on supplementary cementitious materials in cement	t cli/t cem, %	95
raw meal/clinker factor	t RM/t cli, ---	1.55
fuels: (validated to fuel energy requirement)		
- fossil fuel (coal)	% thermal energy	93.6
- alternative fossil fuels	% thermal energy	4.4
- alternative biomass fuels	% thermal energy	2.0
specific fuel energy demand	MJ/t cli	3352
specific electric energy demand	kWh/t cem	102
share of electric energy demand for clinker production	%	50
specific electric energy demand for clinker production	kWh/t cli	70
specific CO ₂ emission of electricity production	t CO ₂ /MWh	0.563 / 0.303 / 0
electric energy cost	€/MWh	93 / 100 / 82
specific electric energy cost for clinker production	€/t cli	6.5
gross CO ₂ per t clinker	kg fossil CO ₂ /t cli	832
process CO ₂ per t clinker	kg fossil CO ₂ /t cli	536
gross CO ₂ per t cement(itious)	kg CO ₂ /t cem	603
gross CO ₂ generation	t fossil CO ₂	1.36 Mio.
biogenic CO ₂ from alternative biomass fuels	t biogenic CO ₂	16,000
fuel costs (coal)	€/t	117 / 117 / 117
energy specific fuel costs (coal)	€/GJ	4.5 / 4.5 / 4.5
fuel costs (natural gas)	€/GJ	4.4 / 3.6 / 3.2
fuel costs (hydrogen)	€/kg	3.2 / 2.2 / 1.5
fuel costs (hydrogen)	€/GJ	27 / 18 / 12.5
alternative fuel cost	€/t	28 / 28 / 19
alternative fuel cost	€/GJ	1.5 / 1.5 / 1
investment costs	2 Mio. clinker annual capacity	€/t annual capacity Mio. €
		160 320
investment costs	1 Mio. clinker annual capacity	€/t annual capacity Mio. €
		210 210
investment costs	0.5 Mio. clinker annual capacity	€/t annual capacity Mio. €
		310 155
operational costs (excl. depreciation)	€/t cli	21.5
exchange rate for US Dollar/Euro	US \$/€	1.15

7 Annex III: References

General references

European Cement Research Academy; Cement Sustainability Initiative, Ed. *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead*; (CSI/ECRA-Technology Papers 2017). Duesseldorf; Geneva, 2017. Available at: <https://ecra-online.org/research/technology-papers>

European Cement Research Academy; Cement Sustainability Initiative, Ed. *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead (CSI/ECRA-Technology Papers)*. Duesseldorf; Geneva, 2009. Available at: <https://ecra-online.org/research/technology-papers>

Global Cement and Concrete Association, Ed. *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete*. London, 2021. Available at: <https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf>

Global Cement and Concrete Association, GCCA, Hrsg. *GNR 2.0 – GCCA in Numbers* [Access on: 24.08.2022]. Available at: <https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/>

Cembureau, Ed. *Cementing the European Green Deal: Reaching climate neutrality along the cement and concrete value chain by 2050*. Brussels, 2020 [Access on: 24.08.2022]. Available at: https://cembureau.eu/media/kuxd32qi/cembureau-2050-roadmap_final-version_web.pdf

Schneider, Martin. *The cement industry on the way to a low-carbon future*. Cement and Concrete Research. 2019, **124**, 105792

National Cement Industry Association; Brazilian Portland Cement Association, Ed. *Cement technology roadmap: Carbon emissions reduction potential in the Brazilian cement industry by 2050*. Rio de Janeiro, 2019. Available at: <http://snic.org.br/assets/pdf/roadmap/cement-technology-roadmap-brazil.pdf>

International Energy Agency, Ed. *Low-Carbon Transition in the Cement Industry: Technology Roadmap*. Paris, 2018 [Access on: 24.08.2022]. Available at: <https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>

European Bank for Reconstruction and Development, Ed. *Low-Carbon Roadmap for the Egyptian cement industry: Project "Egypt: Technology and policy scoping for a low-carbon Egyptian cement industry"*, 2016. Available at: http://www.thegreenwerk.net/publications/Low_Carbon_Roadmap_for_the_Egyptian_Cement_Industry.html

International Energy Agency; European Cement Research Academy; IEAGHG; Ed. *Deployment of CCS in the Cement Industry: Report:2013/19; December 2013*. Cheltenham, 2013. Available at: http://www.ieaghg.org/docs/General_Docs/Reports/2013-19.pdf

Cement Sustainability Initiative, Ed. *Existing and potential technologies for carbon emissions reductions in the Indian cement industry: A set of technical papers produced for the project "Low carbon technology roadmap for the Indian cement industry"*. Washington, 2013 [Access on: 24.08.2022]. Available at: <https://www.wbcasd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Existing-and-Potential-Technologies-for-Carbon-Emissions-Reductions-in-the-Indian-Cement-Industry>

International Energy Agency, Ed. *Low-Carbon Technology for the Indian Cement Industry: Technology Roadmap*. Paris, 2013 [Access on: 24.08.2022]. Available at: <https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Technology-Roadmap-Low-Carbon-Technology-for-the-Indian-Cement-Industry>

World Business Council for Sustainable Development; International Energy Agency, Ed. *Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050*. Conches-Geneva, 2009 [Access on: 24.08.2022]. Available at: <https://www.iea.org/reports/cement-technology-roadmap-carbon-emissions-reductions-up-to-2050>

European Cement Research Academy; Research Group CEMCAP; Research Group CLEANKER, Ed. *Presentations and Posters of the ECRA/CEMCAP/CLEANKER Workshop 2018 on Carbon Capture Technologies in the Cement Industry* (Brussels 17.10.2018). Available at: <https://ecra-online.org/research/ccs/presentations-and-posters/>

European Cement Research Academy; Research Group CEMCAP, Ed. *Presentations and Posters of the ECRA/CEMCAP Workshop 2017 on Carbon Capture Technologies in the Cement Industry* (6.-7.11.2017). Available at: <https://ecra-online.org/research/ccs/presentations-and-posters/>

European Cement Research Academy, Ed. *ECRA CCS Project: Report on Phase I, II, III, IV.A*. Duesseldorf, 2007, 2009, 2012, 2016. Available at: <http://www.ecra-online.org/research/ccs>

CEMCAP: CO₂ capture from cement production. SINTEF Energy Research [Access on: 24.08.2022]. Available at: <https://www.sintef.no/projectweb/cemcap>

European Cement Research Academy, ECRA, Ed. *ECRA Future Grinding Technologies Project – Report about Phase I: Evaluation of roundtable event*. Duesseldorf, 2015 (Technical Report TR 127/2015). Available at: <http://www.ecra-online.org/research/future-grinding-technologies>

European Cement Research Academy, ECRA, Ed. *CO₂ utilisation: ECRA online seminar (Online 21.06.2022)*. Duesseldorf, 2022

European Cement Research Academy, ECRA, Ed. *Update on carbon capture technology: ECRA online seminar (Online 10.06.2021)*. Duesseldorf, 2021

Ruppert, Johannes; Wagener, Carin; Palm, Sebastian; Scheuer, Wilfried; Hoenig, Volker. *Prozesskettenorientierte Ermittlung der Material- und Energieeffizienzpotentiale in der Zementindustrie: Abschlußbericht; Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit; Forschungskennzahl 3716 36 320 0 FB000170*. Dessau-Roßlau, 2020 (UBA-Texte 48/2020). Available at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-03-06_texte_48-2020_material_energieeffizienz_zementindustrie.pdf

Harder, Joachim. *Development of clinker substitutes*. Zement-Kalk-Gips. 2019, (4), S.40-49

Scrivener, K. L.; John, V. M.; Gartner, E. M. *Eco-efficient cements: Potential, economically viable solutions for a low-CO₂, cement-based materials industry*. Paris, 2016 [Access on: 24.08.2022]. Available at: <https://www.nanocem.org/resources-unep-report/>

Hoenig, V.; Koring, K.; Fleiger, P.; Müller, Ch.; Palm, S.; Reiners, J. *Energy efficiency in cement production*. Cement International. 2013, **11**(3), pp.50-67; (4), pp.46-65

Klein, Henning; Hoenig, Volker. *Model calculations of the fuel energy requirement for the clinker burning process: Modellrechnung zum Brennstoffenergiebedarf des Klinkerbrennprozesses*. Cement International. 2006, **4**(3), pp.44-63

Locher, Friedrich W. *Cement: Principles of production and use*. Duesseldorf, 2005

Cembureau, Hrsg. *World cement production 2020, by region and main countries, % estimations* [Access on: 09.08.2022]. Available at: <https://cembureau.eu/media/lnjpejs2/world-cement-production-in-2020-by-region.jpg>

Cembureau, Hrsg. *About our industry - key facts & figures* [Access on: 09.08.2022]. Available at: <https://cembureau.eu/about-our-industry/key-facts-figures>

The Global Cement Report. 11. Ed. Dorking, Surrey, 2015

Tokheim, Lars-André; Eldrup, Nils; Mathisen, Anette. *CO₂ capture test facility at Norcem Brevik, project phase II, test step 1: Benchmark analysis*. Porsgrunn, 2015 (Tel-Tek report 2213050-4)

Werner, A.; Leibinger, H. *Wärmerückgewinnung und Energieerzeugung bei der Zementklinkerproduktion: Ein energetischer Vergleich*. Cement International. 2014, **12**(06), pp.40-43

Worrell, Ernst; Kermeli, Katerina; Galitsky, Christina. *Energy efficiency improvement and cost saving opportunities for cement making: An ENERGY STAR® guide for energy and plant managers*. Washington, 2013 [Access on: 24.08.2022]. Available at: <https://www.energystar.gov/buildings/tools-and-resources/energy-efficiency-improvement-and-cost-saving-opportunities-cement-making>

Garcia-Garcia, Guillermo; Fernandez, Marta Cruz; Armstrong, Katy; Woollass, Steven; Styring, Peter. *Analytical review of life-cycle environmental impacts of carbon capture and utilization technologies*. ChemSusChem. 2021, **14**(4), S.995-1015. Available at: <https://doi.org/10.1002/cssc.202002126>

Hepburn, Cameron; Adlen, Ella; Beddington, John; Carter, Emily A.; Fuss, Sabine; Mac Dowell, Niall; Minx, Jan C.; Smith, Pete; Williams, Charlotte K. *The technological and economic prospects for CO₂ utilization and removal*. Nature. 2019, **575**(7781), S.87-97. Available at: <https://doi.org/10.1038/s41586-019-1681-6>

Cuéllar-Franca, Rosa M.; Azapagic, Adisa. *Carbon capture, storage and utilisation technologies: a critical analysis and comparison of their life cycle environmental impacts*. Journal of CO₂ Utilization. 2015, **9**, S.82-102

Additional specific references

Technology Paper No. 1: Improving raw mix burnability e.g. through mineralisers

Locher, Friedrich W. *Cement: Principles of production and use*. Duesseldorf, 2005

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

Locher, Friedrich W. *Cement: Principles of production and use*. Duesseldorf, 2005

Klein, Henning; Hoenig, Volker. *Model calculations of the fuel energy requirement for the clinker burning process*. Cement International. 2006, **4**(3), pp.44-63

Technology Paper No. 3: Preheater modification through cyclones with lower pressure drop

Worrell, Ernst; Kermeli, Katerina; Galitsky, Christina. *Energy efficiency improvement and cost saving opportunities for cement making: An ENERGY STAR® guide for energy and plant managers*. Washington, 2013

Nielsen, Mads; Skaerlund Petersen, Anders. *Capacity boost and energy savings: With counter current heat exchanging cyclone*. In: VDZ, Ed. 8th International VDZ Congress 2018; Proceedings (Duesseldorf 26–28 September 2018). Duesseldorf, 2018, pp.454-467

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

Klein, Henning; Hoenig, Volker. *Model calculations of the fuel energy requirement for the clinker burning process*. Cement International. 2006, **4**(3), pp.44-63

Technology Paper No. 5: Increase of kiln capacity

Klein, Henning; Hoenig, Volker. *Model calculations of the fuel energy requirement for the clinker burning process*. Cement International. 2006, **4**(3), pp.44-63

Technology Paper No. 6: Retrofit mono-channel burner to modern multi-channel burner

Worrell, Ernst; Kermeli, Katerina; Galitsky, Christina. *Energy efficiency improvement and cost saving opportunities for cement making: An ENERGY STAR® guide for energy and plant managers*. Washington, 2013

Guse, Bodo. *Multi-fuel burner flexibility*. International Cement Review. 2006, (6), pp.35-36

Technology Paper No. 7: Oxygen enrichment technology

Laux, Stefan; Mocsari, Jeffrey; Webel, Markus; Hope, Stephen. *Benefits of oxygen injection*. International Cement Review. 2009, (1), pp.66-67

Leger, C.B.; Friday, J. *Oxygen enrichment for cement kiln firing*. In: IEEE, Ed. 43rd IEEE-IAS/PCA Cement Industry Technical Conference (Vancouver 29.04.-03.05.2001)

Hoenig, Volker. *Prozessstabilisierung bei hohem Sekundärbrennstoffeinsatz durch Sauerstoffeindüsung bei Drehofenanlagen der Zementindustrie: Schlussbericht zu dem IGF-Vorhaben 16980 N*. Duesseldorf: Forschungsinstitut der Zementindustrie GmbH, 2015 (IGF-Forschungsvorhaben; AIF-Forschungsvorhaben 16980 N)

Technology Paper No. 8: Efficient clinker cooler technology

Latest generation high efficiency clinker coolers: Technical paper no. 2. In: Cement Sustainability Initiative (CSI), Ed. Existing and potential technologies for carbon emissions reductions in the Indian

cement industry: A set of technical papers produced for the project "Low carbon technology roadmap for the Indian cement industry". Washington: World Bank, 2013, pp.16-17

Conversion to reciprocating grate cooler for clinker making in rotary kilns. In: Galitsky, Christina; Price, Lynn; Zhou, Nan; Zhou, Fuqiu; Xiong, Huawen; Zeng, Xuemin; Wang, Lan. Guidebook for using the tool BEST Cement: Benchmarking and energy savings tool for the cement industry. Berkeley, 2008, pp.42-43

International Energy Agency, IEA, Ed. *Cement production (Energy demand technologies data)*, 2010 (IEA ETSAP Technology Brief I03) [Access on: 22.08.2022] Available at: <http://iea-etsap.org/index.php/energy-technology-data/energy-demand-technologies-data>

Clinker cooling. In: Institute for industrial productivity, Ed. Industrial efficiency technology database [online] [Access on: 22.08.2022]. Available at: <http://www.iipinetwork.org/wp-content/letd/content/clinker-cooling.html>

Harder, Joachim. *Latest trends in clinker cooling.* Zement-Kalk-Gips. 2011, (3), pp.33-42

Bordei, Valentina. *Optimising cooler operation.* World Cement. 2020, (7), S.27-30

Technology Paper No. 9: Waste heat recovery: Steam

Ino, Tatsuo. *Waste Heat Recovery Power Generation (WHRPG) for cement plants.* In: Verein Deutscher Zementwerke, Ed. Process Technology of Cement Manufacturing: 6th International VDZ Congress (Duesseldorf 30.09.-02.10.2009). Duesseldorf, 2009, pp.166-173

Technology Paper No. 10: Waste heat recovery: ORC

Baatz, Eduard. *Verstromung von Niedertemperaturabwärme mit Hilfe einer ORC-Anlage (Organic-Rankine-Cycle) im Zementwerk Lengfurt: Investitionen zur Verminderung von Umweltbelastungen.* Heidelberg, 1999

Claus, W.; Kolbe, T. *Langzeitbetriebserfahrungen mit der ORC-Anlage zur Niedertemperaturverstromung im Werk Lengfurt.* Zement-Kalk-Gips. 2002, **55**(10), pp.78-86

Claus, Wolfgang; Kolbe, Thomas. *Long-term operating experience with the ORC plant for low temperature power generation at the Lengfurt Works.* In: Verein Deutscher Zementwerke, Ed. Process Technology of Cement Manufacturing: 5th International VDZ Congress 2002 (Duesseldorf 23.-27.09.2002). Duesseldorf, 2003, pp.264-272

Ferrari, F. *Heat recovery system: Features of Ait Baha project.* CTG Italcementi Group, 2011

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

Mirolli, M.D. *Kalina Cycle power systems in waste heat recovery applications.* Global Cement Magazine. 2012, (7-8), pp.38-45

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

Alternative raw materials. In: Industrial efficiency technology database [online] [Access on: 22.08.2022]. Available at: <http://www.iipinetwork.org/wp-content/letd/content/alternative-raw-materials.html>

Alternative de-carbonated raw materials for clinker production: Technical paper no. 18. In: Cement Sustainability Initiative, Ed. Existing and potential technologies for carbon emissions reductions in the Indian cement industry: A set of technical papers produced for the project "Low carbon technology roadmap for the Indian cement industry". Washington, 2013, pp.60-61

Technology Paper No. 13: Fuel switch (coal/petcoke →oil/gas)

Umweltbundesamt; Deutsche Emissionshandelsstelle, Ed. *Einheitliche Stoffwerte für Emissionsfaktoren, Heizwerte und Kohlenstoffgehalte für Brennstoffe, Rohstoffe und Produkt: Anhang 1 zur Verordnung über die Zuteilung von Treibhausgas-Emissionsberechtigungen in der Zuteilungsperiode 2008 bis 2012 vom 13.08.2007, 2007* [Access on: 23.08.2022]. Available at: https://www.gesetze-im-internet.de/zuv_2012/anhang_1.html

Seidl, Ingrid. *CO₂-Trading aus betrieblicher und wirtschaftlicher Sicht.* In: Istituto Veneto di Scienze, Lettere ed Arti, Ed. 2. Internationale Umweltkonferenz im Rahmen der Programme INTERREG IIIA Österreich – Italien mit Unterstützung der Republik Slowenien Interreg IIIA Italien – Slowenien, Projekt Joint Ventures für Umwelt und Wirtschaft ECOJOINTS zum Thema "Luft" (Venice 30.10.2006)

Technology Paper No. 14: Alternative fuels replacing conventional fossil fuels

vdz-Lernplattform: VDZ gGmbH, © 2008 [Access on: 23.08.2022] Available at: <http://www.elearning-vdz.de>

Increasing thermal Substitution Rate (TSR) in Indian cement plants to 30%: Technical paper no. 11. In: Cement Sustainability Initiative, Ed. Existing and potential technologies for carbon emissions reductions in the Indian cement industry: A set of technical papers produced for the project "Low carbon technology roadmap for the Indian cement industry". Washington, 2013, pp.38-44

Albino, Vito; Dangelico, Rosa M.; Natalicchio, Angelo; Yazan, Devrim M. *Alternative energy sources in cement manufacturing: A systematic review of the body of knowledge.* London, 2011

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

Theulen, Jan. *HeidelbergCement-Waste processing achievements in Asia.* Global Cement Magazine. 2012, (1), pp.14-16

Trenkwalder, J. *Waste heat recovery for the drying of sewage sludge.* Cement International. 2010, **8**(4), pp.48-53

Sawecki, Jaroslaw. *Improved RDF Quality and Combustion due to the Drum Drier, Chelm, Poland.* In: Verein Deutscher Zementwerke, Ed. Process Technology of Cement Manufacturing: 7th International VDZ Congress; Proceedings (Duesseldorf 25.-27.09. 2013.) Duesseldorf: Verl. Bau und Technik, 2013, pp.176-177

Trenkwalder, J.; Schwörer, W. *BGS-Trocknung in den Zementwerken Bernburg und Karlstadt*. In: VDZ-Fachtagung Zement-Verfahrenstechnik (Duesseldorf 12.02.2020). Duesseldorf, 2020

Leitão, Francisco. *Drying high moisture RDF at Souselas*. In: VDZ, Ed. 8th International VDZ Congress 2018; Proceedings (Duesseldorf 26.-28.09.2018) Duesseldorf, 2018, pp.416-433

Voges, U. *The V-mill - a new option for producing kiln-ready replacement fuels*. Cement International. 2018, **16**(3), pp.44-49

Krammer, Regina; Uttinger, Johannes. *Processing alternative fuels in a rocket mill: First operating experiences*. Global Cement Magazine. 2014, (10), pp.10-14

Kastner, C.; Uttinger, H. *The A TEC Rocket Mill for maximizing solid alternative fuel firing*. Cement International. 2017, **15**(4), S.52-56

Neuwirth, Thomas. *Ersatzbrennstoffaufbereitung mit Rocket Mill, Wietersdorf*. In: VDZ-Fachtagung Zement-Verfahrenstechnik (Duesseldorf 04.02.2016). Duesseldorf, 2016

Technology Paper No. 16: Pre-combustion chambers and gasification

Schmidt, Thomas. *Experience report: Burning chamber PREPOL SC after two years of operation*. In: ecra, Ed. State-of-the-Art Calciner Technology (Online 26.11.2020). Duesseldorf, 2020

Leibinger, Helmut. *Experience with the KHD PYROROTOR in the SPZ Gmunden plant, CEM2020 - GM*. In: ecra, Ed. State-of-the-Art Calciner Technology (Online 26.11.2020). Duesseldorf, 2020

Nielsen, Mads. *20 years of HOTDISC experience*. In: ecra, Ed. State-of-the-Art Calciner Technology (Online 26.11.2020). Duesseldorf, 2020

Abualteen, Hisham. *Experiences with a circulating fluidized bed (CFB)-gasifier in Cemex' cement plant Rüdersdorf/Germany*. In: ecra, Ed. State-of-the-Art Calciner Technology (Online 26.11.2020). Duesseldorf, 2020

Jensen, Lars S. *Practical experiences with the HOTDISK and FLSmidth calciner solutions for alternative fuels*. In: European Cement Research Academy, Ed. Impacts of secondary fuel combustion (Mannersdorf 24.-25.06.2009)

Menzel, Karl. *Polysius Concepts for Secondary Fuels in the Calciner*. In: European Cement Research Academy, Ed. Impacts of secondary fuel combustion (Mannersdorf 24.-25.06.2009)

Tietze, Uta. *Einsatzmöglichkeiten für gefährliche Abfälle im Zementwerk Rüdersdorf*. In: Sonderabfallgesellschaft Berlin-Brandenburg. Thermische Verfahren der Abfallentsorgung (Potsdam 20.01.2010) [Access on: 23.08.2022]. Available at: <https://www.sbb-mbh.de/de/publikationen/seminar-unterlagen/veranstaltungen-bis-2020/>

Lehrmann, Falko. *Überblick über die thermische Klärschlammbehandlung: Trocknung, Monoverbrennung und Mitverbrennung*. In: Thomé-Kozmiensky, K. J.; Beckmann, M., Ed. Energie aus Abfall, Band 10. Neuruppin, 2013, pp.901-926

Metallgesellschaft AG, Ed. *Verfahren zur Herstellung von Zement: Europäische Patentschrift*: Europäisches Patentamt, 1999 (EP 561436 B1)

Bolhàr-Nordenkamp, Markus; Isaksson, Juhani. *Refuse derived fuel gasification technologies for high efficient energy production*. In: Thomé-Kozmiensky, K. J.; Thiel, Stephanie, Ed.: *Waste management*, Vol. 4. Neuruppin: TK Verlag, 2014, pp.379-388

Verein Deutscher Zementwerke, Ed. *Biomass gasification in the cement clinker production - Technoeconomic analysis of future market development: Report on the main energy efficiency*; EDEFU No. 8.5, grant agreement no. 246335, 2014, confidential

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

Vogel, Frédéric. *Hydrothermale Karbonisierung (HTC)*. In: Kaltschmitt, Martin; Hartmann, Hans; Hofbauer, Hermann, Ed. *Energie aus Biomasse: Grundlagen, Techniken und Verfahren*. 3., aktual., u. erw. Berlin: Springer, 2016, pp.1284-1297

De Mena Pardo, B.; Doyle, L.; Renz, M.; Salimbeni, A., Ed. *Industrial Scale Hydrothermal Carbonization: new applications for wet biomass waste*. Bremerhaven: ttz Bremerhaven, 2016 [Access on: 05.10.2016] Available at: <http://www.newapp-project.eu/en/public-library/send/2-public-library/3-industrial-scale-hydrothermal-carbonization-new-applications-for-wet-biomass-waste.html>

Kläusli, Thomas M. *Studie bestätigt Vorteile der Hydrothermalen Carbonisierung von Klärschlamm: Study confirms the benefits of Hydro-thermal Carbonisation of sewage sludge*. Müll und Abfall. 2014, **46**(3), pp.144-150

Fachagentur Nachwachsende Rohstoffe e.V., FNR, Ed. *Hydrothermale Carbonisierung (Berlin, Karlsruhe 11.-12.02.2009, 02.-03.09.2009)*. Gülzow: Fachagentur Nachwachsende Rohstoffe e.V., FNR, 2010 (Gülzower Fachgespräche 33) [Access on: 05.10.2016] Available at: http://www.fnr-server.de/ftp/pdf/literatur/pdf_366-gf_33_hydrothermale.pdf

AVA-CO₂, Ed. *Klärschlamm nutzen - Energie gewinnen: Hydrothermale Carbonisierung*. Zug: AVA-CO₂, 2016 [Access on: 06.10.2016] Available at: http://www.ava-CO2.com/web/media/downloads_DE/broschure/AVA_HTC_Broschuere_DE_2016_web.pdf

Buttmann, Marc. *TerraNova@Ultra-Verfahren zur Klärschlamm-Trocknung mit Phosphor-Rückgewinnung*. In: Holm, O.; Thomé-Kozmiensky, E.; Quicker, P.; Kopp-Assenmacher, S., Ed. *Verwertung von Klärschlamm*. Neuruppin, 2018

Krebs, R. *Weiterentwicklung der hydrothermalen Karbonisierung zur CO₂-sparenden und kosteneffizienten Trocknung von Klärschlamm im industriellen Massstab sowie der Rückgewinnung von Phosphor: Schlussbericht UTF 387.21.11./IDM 2006.2423.222*. Zürich: Züricher Hochschule für angewandte Wissenschaften, 2013 [Access on: 06.10.2016] Available at: http://www.ava-CO2.com/web/media/downloads_DE/dokumente/Schlussbericht_BAFU_HTC_2013.pdf

Standard ISO/DIS 17225-8 2022. *Solid biofuels - Fuel specifications and classes - Part 8: Graded thermally treated and densified biomass fuels for commercial and industrial use*

Thrän, Daniela; Witt, Janet; Schaubach, Kay; Kiel, Jaap; Carbo, Michiel; Maier, Jörg; Ndibe, Collins; Koppejan, Jaap; Alakangas, Eija; Majer, Stefan; Schipfer, Fabian. *Moving torrefaction towards market*

introduction: Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. Biomass and Bioenergy. 2016, **89**, pp.184–200

Rebling, Tammo; Oldhafer, Nils; Klonk-Markowis, Fabian; Hintz, Daniel. *Hydrothermale Carbonisierung (HTC) als Alternative zur Klärschlamm-trocknung? Eine energetische Betrachtung für Projekte zur Klärschlammmonverbrennung.* Hannover, 2020. Available at: <https://www.terranova-energy.com/wp-content/uploads/HTC-Eine-energetische-Betrachtung-fuer-Projekte-zur-Klaerschlammmonverbrennung.pdf>

Intergovernmental Panel on Climate Change, Ed. *Climate change 2022 - mitigation of climate change: Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, 2022. Available at: https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_Citation.pdf

Aragón-Briceño, C.I.; Grasham, O.; Ross, A.B.; Dupont, V.; Camargo-Valero, M.A. *Hydrothermal carbonization of sewage digestate at wastewater treatment works: Influence of solid loading on characteristics of hydrochar, process water and plant energetics.* Renewable Energy. 2020, **157**, pp.959-973. Available at: <https://www.sciencedirect.com/science/article/pii/S0960148120307199>

Aragon-Briceño, Christian; Pozarlik, Artur; Bramer, Eddy; Brem, Gerrit; Wang, Shule; Wen, Yuming; Yang, Weihong; Pawlak-Kruczek, Halina; Niedzwiecki, Lukasz; Urbanowska, Agnieszka; Moscicki, Krzysztof; Ploszczyca, Michal. *Integration of hydrothermal carbonization treatment for water and energy recovery from organic fraction of municipal solid waste digestate.* Renewable Energy. 2022, **184**, pp.577-591

Technology Paper No. 18: Hydrogen

Sapountzi, Foteini M.; Gracia, Jose M.; Weststrate, C.J.; Fredriksson, Hans O.A.; Niemantsverdriet, J.W. *Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas.* Progress in Energy and Combustion Science. 2017, **58**, pp.1–35. Available at: <https://www.sciencedirect.com/science/article/pii/S0360128516300260?via%3Dihub>

Mineral Products Association; Cinar Ltd; VDZ gGmbH, Ed. *Options for switching UK cement production sites to near zero CO₂ emission fuel - Technical and financial feasibility: Summary report; Feasibility Study for the Department for Business Energy and Industrial Strategy; A report funded by an SBRI Competition, TRN 1674/10/2018.* London, 2019

International Renewable Energy Agency, Ed. *Green hydrogen cost reduction: Scaling up electrolyzers to meet the 1.5°C climate goal.* Abu Dhabi, 2020. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

International Energy Agency, Ed. *Global Hydrogen Review 2021.* Paris, 2021 [Access on: 02.08.2022]. Available at: <https://www.iea.org/reports/global-hydrogen-review-2021>

Koring, Kristina. *CO₂-Emissionsminderungspotential und technologische Auswirkungen der Oxyfuel-Technologie im Klinkerbrennprozess.* Duesseldorf, 2013 (Schriftenreihe der Zementindustrie 79). Clausthal, TU, Diss., 2013

Brown, Andy. *Hydrogen transport* [Access on: 18.08.2022]. Available at: <https://www.thechemicalengineer.com/features/hydrogen-transport>

Hodges, Aaron; Hoang, Anh L.; Tsekouras, George; Wagner, Klaudia; Lee, Chong-Yong; Swiegers, Gerhard F.; Wallace, Gordon G. *A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen*. Nature communications. 2022, **13**, 1304. Available at: <https://doi.org/10.1038/s41467-022-28953-x>

Technology Paper No. 19: Electrification, Plasma and other technologies

Tokheim, Lars-André; Mathisen, Anette; Oi, Lars E.; Jayarathna, Chameera; Eldrup; Nils; Gautestad, Tor. *Combined calcination and CO₂ capture in cement clinker production by use of electrical energy*. In: International CCS Research Centre, Ed. 10th Conference on CO₂ Capture, Transport and Storage (Trondheim 17.-19.06.2019). Trondheim, 2019

Mineral Products Association; VDZ gGmbH, Ed. *State of the art fuel mix for UK cement production to test the path for 'Net Zero' - A technical, environmental and safety demonstration: Summary report; Demonstration for the Department for Business Energy and Industrial Strategy; A report funded by an SBRI Competition TRN 2021/08/2019*. London, 2022

Wilhelmsson, Bodil; Kollberg, Claes; Larsson, Johan; Eriksson, Jan; Eriksson, Magnus. *A feasibility study evaluating ways to reach sustainable cement production via the use of electricity*, 2018 [Access on: 18.08.2022] Available at: https://www.cementa.se/sites/default/files/assets/document/65/default_cemzero_2018_public_version_2.0.pdf.pdf

The LEILAC2 project [Access on: 18.08.2022]. Available at: <https://www.project-leilac.eu/leilac2-project>

Karthaus, Lisa; Schall, Albrecht; Hoenig, Volker. *Electrical clinker production - Literature study: Technical Report P-2018/0285*. Duesseldorf, 2018

Antunes, Monica; Lino Santos, Rodrigo; Pereira, João; Rocha, Paulo; Bayao; Bayão Horta, Ricardo; Colaço, Rogério. *Alternative clinker technologies for reducing carbon emissions in cement industry: A critical review*. Materials. 2019, **15**, 209. Available at: <https://doi.org/10.3390/ma15010209>

Chen, L.; Pershin, L.; Mostaghimi, J. *A New Highly Efficient High-Power DC Plasma Torch*. IEEE Transactions on Plasma Science. 2008, **36**(4), S.1068-1069. Available at: <https://ieeexplore.ieee.org/document/4598949>

Technology Paper No. 20: Recycled concrete fines as raw material for clinker production

Deutscher Ausschuss für Stahlbeton, Ed. *Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierten Gesteinskörnungen nach DIN EN 12620: Teil 1: Anforderungen an den Beton für die Bemessung nach DIN EN 1992-1-1*. Berlin, 2019 (DAfStb-Richtlinie)

Müller, Christoph; Severins, Katrin; Spanka, Gerhard. *Brechsand als Zementhauptbestandteil: Leitlinien künftiger Anwendung im Zement und Beton*. Beton. 2020, (9), pp.336-345

Skocek, Jan; Zajac, Maciej; Ben Haha, Mohsen. *Carbon Capture and Utilization by mineralization of cement pastes derived from recycled concrete*. Nature Scientific Reports. 2020, (10), 5614 [Access on: 14.12.2021]. Available at: <https://doi.org/10.1038/s41598-020-62503-z>

Zajac, Maciej; Skocek, Jan; Skibsed, Jørgen; Ben Haha, Mohsen. *CO₂ mineralization of demolished concrete wastes into a supplementary cementitious material – a new CCU approach for the cement industry*. RILEM Technical Letters. 2021, (6), pp.53-60. Available at:

<https://doi.org/10.21809/rilemtechlett.2021.141>

Verein Deutscher Zementwerke, Ed. *Dekarbonisierung von Zement und Beton: Minderungspfade und Handlungsstrategien; Eine CO₂-Roadmap für die deutsche Zementindustrie*. Duesseldorf, 2020

Technology Paper No. 21: Advanced plant control and AI-supported control systems

Teja, Ravi; Sridhar, P.; Guruprasath, M. *Control and Optimization of a Triple String Rotary Cement Kiln using Model Predictive Control*. IFAC-PapersOnLine (4th IFAC Conference on Advances in Control and Optimization of Dynamical Systems). 2016, **49**(1), S.748-753

Sellitto, Miguel A.; Balugani, Elia; Gamberini, Rita; Rimini, Bianca. *A Fuzzy Logic Control application to the Cement Industry*. IFAC-PapersOnLine (16th IFAC Symposium on Information Control Problems in Manufacturing). 2018, **51**(11), pp.1542-1547. Available at: <https://www.sciencedirect.com/science/article/pii/S2405896318314010>

Weng, M.; Schumacher, M.; Volmer, T. *Application service providing and housekeeping for pyro process digitalisation*. In: ecra, Ed. *Industry 4.0: Process control* (Online 01.12.2021). Duesseldorf, 2021

Stephan, Volker. *Mill control*. In: ecra, Ed. *Industry 4.0: Process control* (Online 01.12.2021). Duesseldorf, 2021

FLSmith, Ed. *Advanced process control for the cement industry: ECS/ProcessExpert* [Access on: 23.08.2022] Available at: https://www.flsmidth.com/-/media/brochures/brochures-products/process-control-and-optimization/ecs-process-expert_cement_en.pdf

Process Control and Optimization in Clinker Making. In: Institute for industrial productivity, Ed. *Industrial efficiency technology database* [online] [Access on: 23.08.2022]. Available at: <http://www.iipinetwork.org/wp-content/letd/content/process-control-and-optimization-clinker-making.html>

Technology Paper No. 22: Variable speed drives for fans

Madloul, N.A.; Saidur, R.; Hossain, M.S.; Rahim, N.A. *A critical review on energy use and savings in the cement industries*. Renewable and Sustainable Energy Reviews. 2011, **15**, pp.2042-2060

Price, Lynn; Hasanbeigi, Ali; Lu, Hongyou; Wang, Lan. *Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China*. Berkeley, 2009

De Almeida, Anibal T.; Ferreira, Fernando J.; Fonseca, Paula; Chretien, Bruno; Falkner, Hugh; Reichert, Jürgen C.; West, Mogens; Nielsen, Sandie B.; Both, Dirk. *VSDs for electric motor systems*. Brüssel, 2000. Available at:

<https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.462.4802&rep=rep1&type=pdf>

Technology Paper No. 23: Auxiliary system efficiency

Berger, Helmut. *Auxiliaries I: Compressed air, fans*. In: European Cement Research Academy, Ed. *Electrical Energy Efficiency* (Ladce 18.-19.05.2010)

Schütz, Franc. *Economical compressed air units in cement works*. In: Verein Deutscher Zementwerke, Ed. *Process Technology of Cement Manufacturing: VDZ-Congress 2002*. Duesseldorf, 2003, pp.437-441

Hoenig, V.; Koring, K.; Fleiger, P.; Müller, Ch.; Palm, S.; Reiners, J. *Energieeffizienz bei der Zementherstellung*. *Cement International*. 2013, **11**(3), pp.50-67; (4)pp.46-65

Compressed air systems. In: Institute for industrial productivity, Ed. *Industrial efficiency technology database [online] [Access on: 23.08.2022]*. Available at: <http://www.iipinetwork.org/wp-content/letd/content/compressed-air-systems-cement-plants.html>

Sandmann, Gerd. *Main consumers in a cement plant*. In: European Cement Research Academy, Ed. *Electrical Energy Efficiency (Ladce 18.-19.05.2010)*

Berger, Helmut. *Energy efficiency*. In: European Cement Research Academy, Ed. *Electrical Energy Efficiency (Ladce 18.-19.05.2010)*

Technology Paper No. 24: Energy management

Standard ISO **50001** 2018. *Energy management systems: requirements with guidance for use*

McKane, Aimee; Desai, Deann; Matteini, Marco; Meffert, William; Williams, Robert; Risser, Roland. *Thinking globally: How ISO 50001 - Energy management can make industrial energy efficiency standard practice*. In: *Timing is everything: Moving investment decisions to energy-efficient solutions; 2009 ACEEE Summer Study on energy efficiency in industry (Niagara Falls 28.-31.07.2009)*. Washington, 2009

Technology Paper No. 25: Optimised cement plant operation with renewable power

European Environment Agency, Ed. *Renewable energy in Europe 2018: Recent growth and knock-on effects*. Luxemburg, 2018 (EEA Report 20/2018)

Ruppert, Johannes; Treiber, Kevin; Rösch, Sebastian; Lindner, Stefan. *Einschätzung des Energieflexibilitätspotentials bei der Zementmahlung*. In: Alexander Sauer, Alexander; Abele, Eberhard; Buhl, Hans Ulrich, Ed. *Energieflexibilität in der deutschen Industrie: Ergebnisse aus dem Kopernikus-Projekt - Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung | SynErgie*. Stuttgart, 2019, pp.695-711

Ruppert, Johannes; Seemann, Stefan; Rösch, Sebastian; Treiber, Kevin. *SynErgie: Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung: Abschlussbericht für das BMBF-Forschungsvorhaben; Schlussbericht Teilvorhaben „Lastflexibilisierung in der Zementindustrie (03SFK3K0)“; 01.09.2016 bis 31.10.2019*. Duesseldorf, 2020

Bundesnetzagentur, Ed. *Monitoring report 2015: In accordance with section 63(3) i. c. w. section 35 EnWG and section 48(3) i. c. w. section 53(3) GWB; Data cut-off date: 10 November 2015, Correction: 21 March 2016*. Bonn, 2016

Technology Paper No. 26: Cement grinding with vertical roller mills and roller presses

European Cement Research Academy, Ed. *ECRA Future Grinding Technologies Project – Report about Phase I: Evaluation of roundtable even*. Duesseldorf, 2015 (Technical Report TR 127/2015).

Available at: <https://ecra->

[online.org/fileadmin/redaktion/files/pdf/ECRA_TR_Future_Grinding_Technologies_Phase_I.pdf](https://ecra-online.org/fileadmin/redaktion/files/pdf/ECRA_TR_Future_Grinding_Technologies_Phase_I.pdf)

Ruppert, Johannes; Wagener, Carin; Palm, Sebastian; Scheuer, Wilfried; Hoenig, Volker. *Prozesskettenorientierte Ermittlung der Material- und Energieeffizienzpotentiale in der Zementindustrie: Abschlußbericht; Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit; Forschungskennzahl 3716 36 320 0 FB000170*. Dessau-Roßlau, 2020 (UBA-Texte 48/2020). Available at:

https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-03-06_texte_48-2020_material_energieeffizienz_zementindustrie.pdf

Seemann, Stefan. *Roller press celebrates 40 years*. International Cement Review. 2017, (12), pp.39-43

Verein Deutscher Zementwerke, Ed. *Zerkleinerung*. Duesseldorf, 2020 (Vt 18)

Harder, Joachim. *Developments in the Global Cement Market*. In: Verein Deutscher Zementwerke, Ed. *Process Technology of Cement Manufacturing: 7th International VDZ Congress; Proceedings* (Duesseldorf 25.-27.09. 2013.) Duesseldorf, 2013, pp.12-18

Technology Paper No. 27: High efficiency separators

Verein Deutscher Zementwerke, Ed. *Zerkleinerung*. Duesseldorf, 2020 (Vt 18)

Worrell, Ernst; Kermeli, Katerina; Galitsky, Christina. *Energy efficiency improvement and cost saving opportunities for cement making: An ENERGY STAR® guide for energy and plant managers*. Washington, 2013

Technology Paper No. 28: Optimisation of operating ball mills

Verein Deutscher Zementwerke, Ed. *Zerkleinerung*. Duesseldorf, 2020 (Vt 18)

Hofler, Colm. *Best practice ball mill optimisation within CRH*. In: Verein Deutscher Zementwerke, Ed. *Process Technology of Cement Manufacturing: 6th International VDZ Congress 2009* (Duesseldorf 30.09.-02.10.2009). - Duesseldorf: Verl. Bau und Technik, 2009, pp.136-139

Fleiger, Philipp M. *Going through the mill*. International Cement Review. 2015, (11), pp.63-67

Technology Paper No. 29: Separate grinding of raw material components

Kakali, G.; Tsvivilis, S. *The effect of intergrinding and separate grinding of cement raw mix on the burning process*. Cement and Concrete Research. 1993, **23**(3), pp.651-662

Technology Paper No. 30: Advanced grinding

Fleiger, Philipp M.; Schneider, Martin; Treiber, Kevin. *Future grinding technologies – ECRA's new research project*. In: Chalmers University of Technology, Ed. 14th European Symposium on Comminution and Classification (Göteborg 07.10.09.2015). Göteborg, 2015

Treiber, Kevin. *ECRA technology database*, 2015

European Cement Research Academy, Ed. *Feasibility study for the production of CEM II and CEM III-cements using multi-stage grinding plants*. Technical Report, unpublished

Technology Paper No. 31: Separate ultra-fine grinding and blending of cements

Verein Deutscher Zementwerke, Ed. *Zerkleinerung*. Duesseldorf, 2020 (Vt 18)

Treiber, Kevin. *Herstellung von Zementen mit separater Feinstmahlung*. Clausthal, 2021. Clausthal, TU, Diss., 2020 Available at: <https://doi.org/10.21268/20210322-0>

Knappert, Jonas. *Herstellung und Optimierung klinkereffizienter Zemente mittels separater Feinstmahlung*. TU Clausthal. Clausthal, TU, Diss., i. prep.

Technology Paper No. 32: Increased cement performance by optimised particle size distribution (PSD)

Diaz, Bruno G.; Benavides, Francisco M. *SCMs (Supplementary cementitious materials): Environmental and qualitative benefits*. International Cement Review. 2022, (3), pp.64-68

Müller, M.; Ludwig, H.-M.; Ben Haha, M.; Zajac, M. *Optimization of multi-component cements containing cement clinker, slag, V-fly ash, limestone*. In: Bauhaus-Universität Weimar (Hrsg): 19. Internationale Baustofftagung Tagungsbericht (Weimar 16.-18.09.2015). Weimar, 2015

Palm, Sebastian; Wolter, Albrecht. *Strength development of multi-composite cements with optimized void filling*. Cement International. 2011, **9**(1), S.56-64

Wolter, Albrecht; Palm, Sebastian. *Aktuelle Entwicklungen von Multikompositzementen und ihren Hauptbestandteilen*. In: Bauhaus-Universität Weimar, Ed. 18. Internationale Baustofftagung (Weimar 12.-15.09.2012). Weimar, 2012 (ibausil: 18), pp.1-11

Technology Paper No. 33: Optimised use of grinding aids

Locher, Friedrich W. *Cement: Principles of production and use*. Duesseldorf, 2005

Technology Paper No. 34: Reduction of clinker content in cement by use of granulated blast furnace slag

Ehrenberg, Andreas. *Granulated blast furnace slag - From laboratory into practice*. In: China Building Materials Academy, Ed. 14th International congress on the chemistry of cement, ICCC (Beijing 13.-16.10.2015). Beijing, 2015

Van Oss, Hendrik G. *Iron and steel slag*. In: U.S. Geological Survey, Ed. Mineral commodity summaries 2015. Reston, VA, 2015, pp.82-83 [Access on: 11.11.2016]. Available at: http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf#steel_slag/index.html#pubs

Ehrenberg, Andreas. *New cement resources from the metallurgical industry*. In: ecra, Ed. The Future Composition of Cement and Concrete (Online 30.09.2020). Duesseldorf, 2020

Algermissen, David. *Future slag production in a low carbon steel industry - a break in the circular economy?* In: KU Leuven, Ed. Shifting gears to a climate-neutral & resource efficient society: Proceedings of the 7th international slag valorisation symposium (Leuven 27.-29.04.2021). Leuven, 2021, pp.53-57. Available at: <https://slag-valorisation-symposium.eu/wp-content/uploads/downloads/2021/David%20Algermissen%20-%20Future%20slag%20production%20in%20a%20low%20carbon%20steel%20industry%20-%20A%20break%20in%20the%20circular%20economy.pdf>

Merkel, T. *Daten zur Produktion und Nutzung von Eisenhüttenschlacken im Jahr 2020*. FEhS Report. 2021, **28**, pp.37-38

Technology Paper No. 35: Reduction of clinker content in cement by use of natural pozzolanas

Jasinski, Stephen M., Ed. *Pumice and pumicite*. In: U.S. Geological Survey, Ed. Mineral commodity summaries 2022. Reston, VA, 2022, pp.130-131. Available at: <https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-pumice.pdf>

Harder, Joachim. *Entwicklung der Klinkerersatzstoffe in der Zementindustrie*. Zement-Kalk-Gips. 2006, **59**(2), pp.58-64

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

Standard EN **197-5** 2021. *Cement - Part 5: Portlandcomposite cement CEM II/CM and Composite cement CEM VI*

Standard ASTM C **1897** 2020. *Standard test methods for measuring the reactivity of supplementary cementitious materials by isothermal calorimetry and bound water measurements*

Martirena, Fernando; Scrivener, Karen; Favier, Aurélie, Ed. *Calcined clays for sustainable concrete: Proceedings of the 2nd international conference on calcined clays for sustainable concrete (Havana City 05.-07.12.2017)*. Heidelberg, 2018 (RILEM Bookseries 16)

Bishnoi, Shashank, Ed. *Calcined clays for sustainable concrete: Proceedings of the 3rd international conference on calcined clays for sustainable concrete (New Delhi 15.-17.10.2019)*. Heidelberg, 2020 (RILEM Bookseries 25)

Scrivener, Karen L.; John, Vanderley M.; Gartner, Ellis M. *Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry: Report of UNEP SBCI Working Group on Low-CO₂ Eco-efficient Cement-Based Materials*. Cement and Concrete Research. 2018, **114**, pp.2-26

Martirena, Fernando; Almenares, Roger S.; Zunino, Franco; Alujas, Adrian; Scrivener, Karen. *Color control in industrial clay calcination*. RILEM Technical Letters. 2020, (5), pp.1-7

National Cement Industry Association; Brazilian Portland Cement Association, Ed. *Cement technology roadmap: Carbon emissions reduction potential in the Brazilian cement industry by 2050*. Rio de Janeiro, 2019. Available at: <http://snic.org.br/assets/pdf/roadmap/cement-technology-roadmap-brasil.pdf>

Scrivener, Karen; Favier, Aurélie, Ed. *Calcined clays for sustainable concrete: Proceedings of the 1st international conference on calcined clays for sustainable concrete (Lausanne 23.-25.06.2015)*. Heidelberg: Springer, 2015 (RILEM Bookseries 10)

Karym, H.; Chibihi, M. El M.; Benmokhtar, S.; Belaouad, S.; Moutaabbid, M. *Characterisation of the Kaolinite clay minerals (Nador-North Morocco) using infrared spectroscopy and calorimetry of dissolution*. International Journal of Recent Scientific Research. 2015, **6**(6), pp.4444-4448

Technology Paper No. 37: Reduction of clinker content in cement by use of limestone or other materials

Panesar, Daman K.; Zhang, Runxiao. *Performance comparison of cement replacing materials in concrete: Limestone fillers and supplementary cementing materials - A review*. Construction and Building Materials. 2020, **251**, 118866

John, Vanderley M.; Damineli, Bruno L.; Quattrone, Marco; Pileggi, Rafael G. *Fillers in cementitious materials - Experience, recent advances and future potential*. Cement and Concrete Research. 2018, **114**, pp.65-78

Scrivener, Karen L.; John, Vanderley M.; Gartner, Ellis M. *Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry: Report of UNEP SBCI Working Group on Low-CO₂ Eco-efficient Cement-Based Materials*. Cement and Concrete Research. 2018, **114**, pp.2-26

Martirena, F.; Monzó, J. *Vegetable ashes as Supplementary Cementitious Materials*. Cement and Concrete Research. 2018, **114**, pp.57-64

Amran, Mugahed; Fediuk; Roman; Murali, Gunasekaran; Vatin, Nikolai; Karelina, Maria; Ozbakkaloglu, Togay; Krishna, R.S.; Kumar Sahoo, Ankit; Kumar Das, Shaswat; Mishra, Jyotirmoy. *Rice husk ash-based concrete composites: A critical review of their properties and applications*. Crystals. 2021, **11**, 168

Santhosh, Kumar Gedela; Subhani, Sk M.; Bahurudeen, A. *Recycling of palm oil fuel ash and rice husk ash in the cleaner production of concrete*. Journal of Cleaner Production. 2022, **354**, 131736

Alaloul, Wesam S.; Al Salaheen, Marsail; Malkawi, Ahmad B.; Alzubi, Khalid; Al-Sabaeei, Abdunaser M.; Musarat, Muhammad A. *Utilizing of oil shale ash as a construction material: A systematic review*. Construction and Building Materials. 2021, **299**, 123844

Schmidt, T.; Lunk, P.; Scrivener, K. *Portland composite cement using burned oil shale*. In: Bauhaus-Universität Weimar, Ed. 18. Internationale Baustofftagung Tagungsbericht Bd. 1 (Weimar 12.-15.09.2012). Weimar, 2012 (ibautil: 18), pp.206-211

Technology Paper No. 38: Cements with very high limestone content

Algermissen, D. *Future slag production in a low carbon steel industry*. In: Thiel, Stephanie; Thome-Kozmiensky, Elisabeth; Senk, Dieter G.; Wotruba, Hermann; Antrekowitsch, Helmut; Pomberger, Roland. *Mineralische Nebenprodukte und Abfälle 7: Aschen, Schlacken, Stäube und Baurestmassen*. Neuruppin, 2020, pp.182-191

Algermissen, David. *Future slag production in a low carbon steel industry - a break in the circular economy?* In: KU Leuven, Ed. *Shifting gears to a climate-neutral & resource efficient society: Proceedings of the 7th international slag valorisation symposium (Leuven 27.-29.04.2021)*. Leuven, 2021, pp.53-57 [Access on: 09.08.2022]. Available at: <https://slag-valorisation-symposium.eu/wp-content/uploads/downloads2021/David%20Algermissen%20-%20Future%20slag%20production%20in%20a%20low%20carbon%20steel%20industry%20-%20A%20break%20in%20the%20circular%20economy.pdf>

Palm, Sebastian; Proske, Tilo; Rezvani, Moien; Hainer, Stefan; Müller, Christoph; Graubner, Carl-Alexander. *Cements with a high limestone content – Mechanical properties, durability and ecological characteristics of the concrete*. *Construction and Building Materials*. 2016, **119**, pp.308-318

Palm, Sebastian; Müller, Christoph; Proske, Tilo; Rezvani, Moien; Graubner, Carl-Alexander. *Concrete application of clinker-efficient cements*. *Advances in Cement Research*. 2019, (5), pp.225-234. Available at: <https://doi.org/10.1680/jadcr.17.00217>

Technology Paper No. 39: Impact of very high/very low lime saturation factor

Keienburg, Ralf-Richard. *Kornverteilung und Normfestigkeit von Portlandzement*. Duesseldorf, 1976 (Schriftenreihe der Zementindustrie 42). Karlsruhe, Univ., Diss., 1976

Pöhlmann, Rolf. *Zur Brennbarkeit von Portlandzementrohmehlen in Abhängigkeit von Kalkstandard sowie Zusätzen und der hydraulischen Reaktivität beim Übergang von kalkreichen zu kalkarmen Portlandzementen*. Aachen, 1986. Aachen, RWTH, Diss., 1986

Schiller, Bernd. *Mahlbarkeit der Hauptbestandteile des Zements und ihr Einfluß auf den Energieaufwand beim Mahlen und die Zementeigenschaften*. Duesseldorf, 1992 (Schriftenreihe der Zementindustrie 54). Aachen, TH, Diss., 1992

Taylor, H.F. *Cement chemistry*. 2. ed. London, 1997

Stark, Jochen; Wicht, Bernd. *Zement und Kalk: Der Baustoff als Werkstoff*. Basel, 2000 (Baupraxis)

Technology Paper No. 40: Recycled concrete fines as a cement constituent

Deutscher Ausschuß für Stahlbeton, Ed. *Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierten Gesteinskörnungen nach DIN EN 12620: Teil 1: Anforderungen an den Beton für die Bemessung nach DIN EN 1992-1-1*. Berlin, 2019 (DAfStb-Richtlinie)

Müller, Christoph; Severins, Katrin; Spanka, Gerhard. *Brechsand als Zementhauptbestandteil: Leitlinien künftiger Anwendung im Zement und Beton*. *Beton*. 2020, (9), pp.336-345

Skocek, Jan; Zajac, Maciej; Ben Haha, Mohsen. *Carbon Capture and Utilization by mineralization of cement pastes derived from recycled concrete*. Nature Scientific Reports. 2020, (10), 5614 [Access on: 14.12.2021]. Available at: <https://doi.org/10.1038/s41598-020-62503-z>

Zajac, Maciej; Skocek, Jan; Skibsed, Jørgen; Ben Haha, Mohsen. *CO₂ mineralization of demolished concrete wastes into a supplementary cementitious material – a new CCU approach for the cement industry*. RILEM Technical Letters. 2021, (6), pp.53-60. Available at: <https://doi.org/10.21809/rilemtechlett.2021.141>

Verein Deutscher Zementwerke, Ed. *Dekarbonisierung von Zement und Beton: Minderungspfade und Handlungsstrategien; Eine CO₂-Roadmap für die deutsche Zementindustrie*. Duesseldorf, 2020

Technology Paper No. 41: Reduction of clinker content in cement by use of fly ash

Zhang, Xing. *Management of coal combustion wastes*. Paris, 2014 (CCC/231). Available at: <https://usea.org/publication/management-coal-combustion-wastes-ccc231>

International Energy Agency, IEA, Ed. *Net Zero by 2050: A Roadmap for the Global Energy Sector* Paris, 2021. Available at: <https://www.iea.org/reports/net-zero-by-2050>

Bhatt, Arpita; Priyadarshini, Sharon; Acharath Mohanakrishnan, Aiswarya; Abri, Arash; Sattler, Melanie; Techapaphawit, Sorakrich. *Physical, chemical, and geotechnical properties of coal fly ash: A global review*. Case Studies in Construction Materials. 2019, **11**, e00263. Available at: <https://www.sciencedirect.com/science/article/pii/S2214509518303735>

Verein Deutscher Zementwerke, Ed. *Zerkleinerung*. Duesseldorf, 2020 (Vt 18)

Yao, Z.T.; Ji, X.pp.; Sarker, P.K.; Tanga, J.H.; Ge, L.Q.; Sia, M.pp.; Xia, Y.Q. *A comprehensive review on the applications of coal fly ash*. Earth-Science Reviews. 2015, **141**, pp.105-121

Technology Paper No. 42: Reduction of CO₂ by efficient use of concrete

Bundesverband Spannbeton-Fertigdecken, Ed. *Die Zukunft Spannbeton-Fertigdecken: schnell – flexibel – wirtschaftlich*. Berlin, 2019. Available at: https://www.spannbeton-fertigdecken.de/images/BVSF-Imagebroschuere_2019.pdf

Frenzel, Michael; Zschau, Nadine. *Precast components with carbon reinforced concrete: “BOX” prototype*. Concrete Plant International. 2020, (5), pp.146-157

Wagner, Juliane; Würgau, Carolin; Schumann, Alexander; Schütze, Elisabeth; Ehlig, Daniel; Nietner, Lutz; Curbach, Manfred. *Strengthening of Reinforced Concrete Structures with Carbon Reinforced Concrete: Possibilities and Challenges*. CivilEng. 2022, pp.400-426

Flatt, Robert J.; Wangler, Timothy, Ed. *Digital Concrete 2018: Special Issue*. Cement and Concrete Research. 2018, **112**. Available at: <https://www.sciencedirect.com/journal/cement-and-concrete-research/special-issue/10W6F4DB63B>

Küppers, Mark, Ed. *Digital Concrete 2020: Sonderheft*. CPT Worldwide - Construction Printing Technology. 2020, (2), pp.1-71. Available at: https://digitalconcrete2020.com/wp-content/uploads/2020/07/2002_CPT_DC.a.pdf

Global Cement and Concrete Association, Ed. *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete*. London, 2021. Available at: <https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf>

Technology Paper No. 43: Alkali-activated binders

Shobeiri, Vahid; Bennett, Bree; Xie, Tianyu; Visintin, Phillip. *A comprehensive assessment of the global warming potential of geopolymer concrete*. Journal of Cleaner Production. 2021, **297**, 126669. Available at: <https://www.sciencedirect.com/science/article/pii/S0959652621008891>

Davidovits, Joseph. *Geopolymer: Chemistry & Applications*. Saint-Quentin: Institut Géopolymère, 2008

Provis, John L. *Geopolymers and other alkali activated materials: Why, how, and what?* Materials and Structures/Materiaux et Constructions. 2014, **47**(01-02), pp.11-25

Gartner, E.M. *Potential improvements in cement sustainability: Paper Number 15*. In: Novel Developments and Innovation in Cementitious Materials: 31st Cement and Concrete Science Conference (London 12.-13.09.2011). London, 2011

The geopolymer solution: Zeobond Pty Ltd., © 2012 [Access on: 24.08.2022]. Available at: <http://www.zeobond.com/geopolymer-solution.html>

Buchwald, Anja; Dombrowski, Katja; Weil, Marcel. *Geopolymer binders: Part 1 - What are geopolymers; Part 2 - Development and optimization of geopolymer concrete mixtures for strong and durable external wall units; Part 3 - Ecological and economic analyses of geopolymer concrete mixes for external structural elements*. Zement-Kalk-Gips. 2007, **60**(12), pp.78-84; 2008, **61**(3), pp.70-80; 2011, **64**(7-8), pp.76-87

McLellan, Benjamin C.; Williams, Ross P.; Lay, Janine; Van Riessen, Arie; Corder, Glen D. *Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement*. Journal of Cleaner Production. 2011, **19**(9-10), pp.1080-1090

Technology Paper No. 44: Cements based on carbonation of calciumsilicates

Lothenbach, Barbara; Matschei, Thomas; Möschner, Göril; Glasser, Fred P. *Thermodynamic modelling of the effect of temperature on the hydration and porosity of Portland cement*. Cement and Concrete Research. 2008, **38**(1), pp.1-18

Hoshino, Seiichi; Yamada, Kazuo; Hirao, Hiroshi. *XRD / Rietveld analysis of the hydration and strength development of slag and limestone blended cement*. Journal of Advanced Concrete Technology. 2006, **4**(2), pp.357-367

Weerd, K. de; Kjellsen, K.O.; Sellevold, E.; Justnes, H. *Synergy between fly ash and limestone powder in ternary cements*. Cement & Concrete Composites. 2011, **33**(1), pp.30-38

Institut National Polytechnique de Toulouse, Ed. *Composition de ciment hydraulique à base decarbonates de calcium: Date de dépôt: 03.10.2001*. Paris, 2001 (FR 2830249 B1)

Hosoi, K.; Hashida, T.; Takahashi, H.; Yamasaki, N.; Korenaga T. *Low-temperature solidification of calcium-carbonate through Vaterite-Calcite wet transformation*. Journal of Materials Science Letters. 1996, **15**(9), pp.812-814

Huijgen, Wouter J.; Witkamp, Geert-Jan; Comans, Rob N. *Mechanisms of aqueous wollastonite carbonation as a possible CO₂ sequestration process*. Chemical Engineering Science. 2016, **61**(13), pp.4242-4251

Daval, Damien; Martinez, Isabelle; Corvisier, Jérôme; Findling, Nathaniel; Goffé, Bruno; Guyota, Francois. *Carbonation of Ca-bearing silicates, the case of wollastonite: Experimental investigations and kinetic modeling*. Chemical Geology. 2009, **262**(6), pp.262-277

Berger, R.L.; Bukowski, J.M. *Reactivity and strength development of CO₂ activated non-hydraulic calcium silicates*. Cement and Concrete Research. 1979, **9**(1), pp.57-68

Schuler, Tom; DeCristofaro, Nicholas. *Sustainable innovation on the road to market: Moving from the lab to global impact for the cement and concrete industries*. In: Jones, Roderick, Ed. Environment, efficiency and economic challenges for concrete: 9th International Concrete Conference (Dundee 04.-06.07.2016)

Sahu, Sada; DeCristofaro, Nicholas. *Part one of a two-part series exploring the chemical properties and performance results of sustainable Solidia Cement™ and Solidia Concrete™: December 17, 2013*. Piscataway, NJ, 2013

Jain, Jitendra; Deo, Omkar; Sahu, Sada; DeCristofaro, Nicholas. *Part two of a series exploring the chemical properties and performance results of sustainable Solidia Cement™ and Solidia Concrete™: February 19, 2014*. Piscataway, NJ, 2014

Technology Paper No. 45: Other low carbonate clinkers: Pre-hydrated calcium silicates

Butt, Ju.M.; Raschkowitsch, L.N.; Heiker, D.M.; Maier, A.A.; Goratschewa, O.I. *Die Bedingungen für die Bildung von Kalziumhydrosilikaten und deren Eigenschaften*. Silikattechnik. 1961, **12**(6), pp.281-287

Ishida, Hideki; Mabuchi, Katsumi; Sasaki, Kaori; Mitsuda, Takeshi. *Low-temperature synthesis of beta-Ca₂SiO₄ from hillebrandite*. American Ceramic Society: Journal. 1992, **75**(9), pp.2427-2432

Ishida, Hideki; Yamazaki, Satoru; Sasaki, Kaori; Okada, Yoshihiko; Mitsuda, Takeshi. *a-Dicalcium Silicate Hydrate: Preparation, Decomposed Phase, and Its Hydration*. American Ceramic Society: Journal. 1993, **76** (7), pp.1707-1712

Link, T.; Bellmann, F.; Ludwig, H.M.; Ben Haha, M. *Low temperature belite binder*. In: China Building Materials Academy, Ed. 14th International congress on the chemistry of cement, ICCB (Beijing 13.-16.10.2015). Beijing, 2015

Stemmermann, P.; Schweike, U.; Garbev, K.; Beuchle, G.; Möller, H. *Celitement - a sustainable prospect for the cement industry*. Cement International. 2010, **8**(5), pp.52-66

Möller, Hendrik. *Celitement - Where do we stand?* In: Verein Deutscher Zementwerke, Ed. Process Technology of Cement Manufacturing: 7th International VDZ Congress; Proceedings (Duesseldorf 25.-27.09. 2013.) Duesseldorf, 2013, pp.219-222

<https://celitement.de/faq/>

Technology Paper No. 46: Other low carbonate cements - Belite cements

Stark, J.; Müller, A.; Rümpler, K.; Seydel, R.; Jost, K. *Produzione di cemento alla belite attiva al fini della riduzione del consumo di energia*. Il Cemento. 1987, **84**(3), pp.239-250

Uchikawa, Hiroshi. *Management strategy in cement technology for the next century*. World Cement. 1994, **25**(10), pp.49-56

Wolter, A. *Belite cements and low-energy clinker*. Cement International. 2005, **3**(6), pp.107-117

Popescu, C.D.; Muntean, M.; Sharp, J.H. *Industrial trial production of low energy belite cement*. Cement & Concrete Composites. 2003, **25**(7), pp.689-693

Locher, Friedrich W. *Cement: Principles of production and use*. Duesseldorf, 2005

Chatterjee, A.K. *High belite cements: present status and future technological options*. Cement and Concrete Research. 1996, **26**(8), pp.1213-1237

Sui, Tongbo; Fan, Lei; Wen, Zhajun; Wang, Jing; Zhang, Zhonglun. *Study on the properties of high strength concrete using high Belite cement*. Journal of Advanced Concrete Technology. 2004, **2**(2), pp.201-206

Technology Paper No. 47: Other low carbonate clinkers: (Belite) calcium sulfoaluminate clinker

Pera, J.; Ambroise, J. *New applications of calcium sulfoaluminate cement*. Cement and Concrete Research. 2004, **34**(4), pp.671-676

Sharp, J.H.; Lawrence, C.D.; Yang, R. *Calcium sulfoaluminate cements-low-energy cements, special cements or what?* Advances in Cement Research. 1999, **11**(1), pp.3-13

Mehta, P.K. *Mechanism of expansion associated with ettringite formation*. Cement and Concrete Research. 1973, **3**(1), pp.1-6

Muzhen, Su; Kurdowski, Wieslaw; Sorrentino, F. *Development in non-portland cements*. In: 9th International Congress on the Chemistry of Cement 1992; Vol. 1 - Congress reports (New Delhi 23.-28.11.1992). New Delhi, 1992, pp.317-354

Beretka, Julius; Sherman, Natalie; Marroccoli, Milena; Pompo, Antonella; Valenti, Gian L. *Effect of composition on the hydration properties of rapid-hardening sulfoaluminate cements: Hydration kinetics and microstructure development*. In: Justnes, Harald, Ed. Proceedings of the 10th International Congress on the Chemistry of Cement: Vol. 2 - Cement hydration (Göteborg 02.-06.06.1997). Göteborg, 1997

Gartner, Ellis; Li, Guanshu. *Clinker sulfoalumineux a haute teneur en belite, procede de fabrication d'un tel clinker et son utilisation pour la preparation de liants hydrauliques*. 2006 (Patent WO 2006/018569 A2)

Canonico, F.; Bernardo, G.; Buzzi, L.; Paris, M.; Telesca, A.; Valenti, G.L. *Microstructural investigations on hydrated high-performance cements based on calcium sulfoaluminate*. In: Beaudoin, J.J.; Makar, J.M.; Raki, L., Ed. 12th International Congress on the Chemistry of Cement, ICC: Papers, posters and abstracts (Montreal 08.-13.07.2007). Montreal, 2007

HeidelbergCement, Ed. *Verfahren zur Herstellung von Ternesit-Belit-Calciumsulfoaluminat-Klinker: Method for producing Ternesite-Belite Calcium Sulfoaluminate clinker (21.02.2016)*. 2013 (Patent WO 2013/023731 A3)

Gartner, Ellis M.; Macphee, Donald E. *A physico-chemical basis for novel cementitious binders*. Cement and Concrete Research. 2011, **41**(7), pp.736-749

Amathieu, L.; Bier, T.A.; Scrivener, K.L. *Mechanisms of set acceleration of Portland cement through CAC addition*. In: Mangabhai, R.J.; Glasser, F., Ed. Calcium Aluminate Cements 2001: Proceedings of the International Conference on Calcium Aluminate Cements (CAC) (Edinburgh 16. - 19. July 2001). London, 2001, pp.303-317

Cu, Ping; Beaudoin, James J.; Quinn, Edmond G.; Myers, Robert E.: *Early strength development and hydration of ordinary Portland cement / Calcium aluminate cement pastes*. Advanced Cement Based Materials. 1997, **6**(2), pp.53-58

Lamberet, Séverine. *Durability of ternary binders based on Portland cement, Calcium Aluminate cement and Calcium Sulfate*. Lausanne, 2005. Lausanne, TH, Diss., 2005

Pelletier-Chaignat, Laure; Winnefeld, Frank; Lothenbach, Barbara; Saout, Gwenn Le; Müller, Christian Jörg; Famy, Charlotte. *Influence of the calcium sulphate source on the hydration mechanism of Portland cement-calcium sulphoaluminate clinker-calcium sulphate binders*. Cement & Concrete Composites. 2011, **33**(5), pp.551-561

Dienemann, Wolfgang; Haha, Mohsen Ben; Bullerjahn, Frank; Schmitt, Dirk. *Belite-Calciumsulfoaluminate- Ternesite (BCT) - a new low-carbon clinker technology*. In: Verein Deutscher Zementwerke, Ed. Process Technology of Cement Manufacturing: 7th International VDZ Congress; Proceedings (Duesseldorf 25.-27.09. 2013.) Duesseldorf, 2013, pp.204-212

Long, A.E.; Basheer, P.A.; Brady, P.; McCauley, A. *A comparative study of three types of controlled permeability formwork liners*. In: Dhir, Ravindra K.; Hewlett, Peter C., Ed. Concrete in the service of mankind; radical concrete technology: Proceedings of the International Conference (Dundee 27.-28.06.1996). London, 1996

Li, G.S.; Walenta, G.; Gartner, E.M. *Formation and Hydration of Low-CO₂ Cement Based on Belite, Calcium Sulfoaluminate and Calcium Aluminoferrite*. In: Beaudoin, J.J.; Makar, J.M.; Raki, L., Ed. 12th International Congress on the Chemistry of Cement, ICC (Montreal 08.-13.07.2007). Montreal, pp.439-455

Buzzi, L.; Canonico, F.; Schäffel, P. *Durability Properties of concrete based industrial calcium sulfoaluminat cement*. In: Norwegian Concrete Association, Ed. Proceedings ICDC 2012, International Congress on Durability of Concrete 2012 (18.-21.06.2012). Trondheim, 2012

Walenta, Günther; Comparet, Cédric; Morin, Vincent. *Lafarge project aether - a new avenue for cement CO₂ mitigation*. Global Cement Magazine. 2013, (5), pp.8-14

Viswanathan, V.N.; Raina, S.J.; Chatterjee, A.K. *An exploratory investigation on Porsal cement*. World Cement. 1978, 9(5-6), pp.109-118

Zakharov, L.A. *Alumina-Belite cement*. In: 6th International Congress on the Chemistry of Cement (Moskau 23.-27.09.1974). Moskau, 1974

Technology Paper No. 48: Oxyfuel technology for carbon capture

European Cement Research Academy, ECRA, Ed. *ECRA CCS Project: Report on Phase I, II, III, IV.A*, Duesseldorf 2007, 2009, 2012, 2016. Available at: <http://www.ecra-online.org/research/ccs>

Voldsund, Mari; Anantharaman, Rahul; Berstad, David; De Lena, Edoardo; Fu, Chao; Gardarsdottir, Stefania; Jamali, Armin; Pérez-Calvo, José-Fransisco; Romano, Matteo; Roussanaly, Simon; Ruppert, Johannes; Stallmann, Olaf; Sutter, Daniel. *D4.6 CEMCAP comparative techno-economic analysis of CO₂ capture in cement plants: WP4 - Comparative capture process analysis*. Trondheim, 2018 (CEMCAP 641185) [Access on: 24.08.2022]. Available at: <https://zenodo.org/record/2597091#.YwY0hllCRph>

Jamali, Armin; Fleiger, Kristina; Ruppert, Johannes; Hoenig, Volker; Anantharaman, Rahul. *D6.1 Optimised operation of an oxyfuel cement plant: CO₂ capture from cement production*. Duesseldorf, 2018 (CEMCAP 641185) [Access on: 09.01.2019] Available at: <https://zenodo.org/record/2597114#.XJox7vZFzeQ>

Lemke, Jost; Willms, Eike. *Clinker production with oxyfuel process without recirculation of the preheater exhaust gases*, 2021 (European Patent Specification EP 3752780 B1). Available at: <https://depatisnet.dpma.de/DepatisNet/depatisnet?action=pdf&docid=EP000003752780B1&xxxfull=1>

Accelerating carbon capture using Oxyfuel technology in cement production, ©2010-2022 [Access on: 12.08.2022]. Available at: <http://ac2ocem.eu-projects.de/>

Unser Projekt - Mit catch4climate CO₂ abscheiden und nutzbar machen, ©2021 [Access on: 12.08.2022]. Available at: <https://catch4climate.com/>

Gimenez, Michel; Paxton, Colin; Wassard, Henrik; Mogensen, Ole; Paubel, Xavier; Leclerc, Mathieu; Cavagne, Patrice, Perrin, Nicolas. *The oxycombustion option*. International Cement Review. 2014, (05), pp.37-43

International Energy Agency; European Cement Research Academy; IEAGHG, Ed. *Deployment of CCS in the Cement Industry*. Cheltenham, 2013 (Report 2013/19). Available at: http://www.ieaghg.org/docs/General_Docs/Reports/2013-19.pdf

World Business Council for Sustainable Development; International Energy Agency, Ed. *Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050*. Conches-Geneva, 2009 [Access on: 24.08.2022]. Available at: <https://www.iea.org/reports/cement-technology-roadmap-carbon-emissions-reductions-up-to-2050>

Technology Paper No. 48: Post-combustion capture using absorption technologies

Voldsund, Mari; Anantharaman, Rahul; Berstad, David; De Lena, Edoardo; Fu, Chao; Gardarsdottir, Stefania; Jamali, Armin; Pérez-Calvo, José-Francisco; Romano, Matteo; Roussanaly, Simon; Ruppert, Johannes; Stallmann, Olaf; Sutter, Daniel. *D4.6 CEMCAP comparative techno-economic analysis of CO₂ capture in cement plants: WP4 - Comparative capture process analysis*. Trondheim, 2018 (CEMCAP 641185) [Access on: 24.08.2022]. Available at:

<https://zenodo.org/record/2597091#.YwY0hllCRph>

Gerbelová, Hana; Van der Spek, Mijndert; Schakel, Wouter. *Feasibility assessment of CO₂ capture retrofitted to an existing cement plant: Post-combustion vs. oxy-fuel combustion technology*. Energy Procedia. 2017, **114**, pp.6141-6149

International Energy Agency, IEA, Ed. *Cost of CO₂ capture in the industrial sector: Cement and iron and steel industries*. Paris, 2018 (IEAGHG Technical Review 2018-TR03) Available at: <http://documents.ieaghg.org/index.php/s/bmx4OIMiBrCYq8c>

Voldsund, Mari; Gardarsdottir, Stefania; De Lena, Edoardo; Pérez-Calvo, Jose-Francisco; Jamali, Armin; Berstad, David; Fu, Chao; Romano, Matteo; Roussanaly, Simon; Anantharaman, Rahul; Hoppe, Helmut; Sutter, Daniel; Mazzotti, Marco; Gazzani, Matteo; Cinti, Giovanni; Jordal, Kristin. *Comparison of Technologies for CO₂ Capture from Cement Production: Part 1 - Technical Evaluation; Part 2 - Cost Analysis*. Energies. 2019, **12**(3)

Absorption. In: Wilcox, Jennifer: Carbon Capture. New York: Springer, 2012, pp.53-114

Stéphenne, Karl. *Start-Up of world's first commercial Post-Combustion coal fired CCS project: Contribution of Shell Cansolv to SaskPower Boundary Dam ICCS project*. Energy Procedia. 2014, **63**, pp.6106-6110

Bjerge, Liv-Margrethe; Brevik, Per. *CO₂ capture in the cement industry, Norcem CO₂ capture project (Norway)*. Energy Procedia. 2014, **63**, pp.6455-6463

Nygaard Knudsen, Jacob; Morten Bade, Otto; Askestad, Inga; Gorset, Oddvar; Mejdell, Thor. *Pilot plant demonstration of CO₂ capture from cement plant with advanced amine technology*. Energy Procedia. 2014, **63**, pp.6464-6475

Perilli, David. *The Skyonic SkyMine: The future of cement plant carbon capture?*. Global Cement Magazine. 2015, (5), pp.8-12

Technology Paper No. 48: Post-combustion capture using membrane processes

Hägg, M.-B.; Lindbrathen, A.; He, X.; Nodeland, S.G.; Cantero, T. *Pilot demonstration-reporting on CO₂ capture from a cement plant using hollow fiber process*. Energy Procedia. 2017, **114**, pp.6150-6165. Available at: <https://www.sciencedirect.com/science/article/pii/S1876610217319549>

Berstad, David; Traedal, Stian. *D11.3 Membrane-assisted CO₂ liquefaction for CO₂ capture from cement plants: WP11 Membrane-assisted CO₂ liquefaction*, 2018 (CEMCAP 641185) Available at: <https://doi.org/10.5281/zenodo.2605082>

Kearns, David; Liu, Harry; Consoli, Chris. *Technology readiness and costs of CCS*. Melbourne, 2021. Available at: <https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf>

Han, Yang; Ho, W.S. *Moving beyond 90% carbon capture by highly selective membrane processes*. Membranes. 2022, **12**, 399. Available at: <https://www.mdpi.com/2077-0375/12/4/399>

Dai, Zhongde; Fabio, Santinelli; Giuseppe Marino, Nardelli; Riccardo, Costi; Deng, Liyuan. *Field test of a pre-pilot scale hollow fiber facilitated transport membrane for CO₂ capture*. International Journal of Greenhouse Gas Control. 2019, **86**, S.191-200. Available at: <https://www.sciencedirect.com/science/article/pii/S1750583619301628>

Roussanaly, Simon. *Calculating CO₂ avoidance costs of Carbon Capture and Storage from industry*. Carbon Management. 2019, **10**(1), S.105-112. Available at: <https://doi.org/10.1080/17583004.2018.1553435>

Membrane technology. In: Wilcox, Jennifer: Carbon Capture. New York: Springer, 2012, pp.177-218

Khalilpour, Rajab; Mumford, Kathryn; Zhai, Haibo; Abbas, Ali; Stevens, Geoff; Rubin, Edward pp. *Membrane-based carbon capture from flue gas: A review*. Journal of Cleaner Production. 2015, **103**, pp.286-300

Freeman, Brice; Hao, Pingjiao; Baker, Richard; Kniep, Jay; Chen, Eric; Ding, Junyuan; Zhang, Yue; Rochelle, Gary T. *Hybrid membrane-absorption CO₂ capture process*. Energy Procedia. 2014, **63**, pp.605-613

Bjerge, Liv-Margrethe; Brevik, Per. *CO₂ capture in the cement industry, Norcem CO₂ capture project (Norway)*. Energy Procedia. 2014, **63**, pp.6455-6463

Lindqvist, Karl; Roussanaly, Simon; Anantharaman, Rahul. *Multi-stage membrane processes for CO₂ capture from cement industry*. Energy Procedia. 2014, **63**, pp.6476-6483

Scholes, C. A.; Ho, M. T.; Aguiar, A. A.; Wiley, D. E.; Stevens, G. W.; Kentish, S. E. *Membrane gas separation processes for CO₂ capture from cement kiln flue gas*. International Journal of Greenhouse Gas Control. 2014, **24**(05), pp.78-86

Technology Paper No. 48: Post-combustion capture - Physical separation processes

Hovington, Pierre; Ghaffari-Nik, Omid; Mariac, Laurent; Liu, Andrew; Henkel, Brett; Marx, Stefan. *Rapid cycle temperature swing adsorption process using solid structured sorbent for CO₂ capture from cement flue gas*. In: 15th Greenhouse Gas Control Technologies Conference, GHGT-15 (Abu Dhabi 15.-18.03.2021). Cheltenham, 2021. Available at: <http://dx.doi.org/10.2139/ssrn.3814414>

Kataria, Atish; Mobley, Paul; Nelson, Thomas; Soukri, Mustapha; Tanthana, Jak; Song, Chunshan; Wang, Dongxiang; Wang, Xiaoxing. *Advanced solid sorbents and process designs for Post-Combustion CO₂ capture (DE-FE0007707)*. In: National Energy Technology Laboratory, Ed. NETL CO₂ Capture Technology Review Meeting (08.-12.08.2016). Albany, Available at: <https://netl.doe.gov/sites/default/files/event-proceedings/2016/c02%20cap%20review/4-Thursday/T-Nelson-RTI-Solid-Sorbent-Based-CO2-Capture.pdf>

Air Liquide, Ed. *Cryocap™ Carbon Capture Technologies* [Access on: 19.08.2022]. Available at: https://www.engineering-airliquide.com/sites/activity_eandc/files/2021/07/20/air-liquide-cryocap-brochure-2021.pdf

Rodrigues, Guillaume. *Cryocap FG - a combination of cryo and adsorption technologies: An alternate path to steam-driven technologies to decrease cost and carbon footprint*. In: ecra, Ed. Update on Carbon Capture Technology (Online 10.06.2021). Duesseldorf, 2021

Riboldi, Luka; Bolland, Olav. *Overview on Pressure Swing Adsorption (PSA) as CO₂ capture technology: State-of-the-art, limits and potentials*. Energy Procedia. 2017, **114**, pp.2390-2400. Available at: <https://doi.org/10.1016/j.egypro.2017.03.1385>

Technology Paper No. 48: CO₂ capture using solid sorbents: Ca looping (CaL)

Voldsund, Mari; Anantharaman, Rahul; Berstad, David; De Lena, Edoardo; Fu, Chao; Gardarsdottir, Stefania; Jamali, Armin; Pérez-Calvo, José-Francis; Romano, Matteo; Roussanaly, Simon; Ruppert, Johannes; Stallmann, Olaf; Sutter, Daniel. *D4.6 CEMCAP comparative techno-economic analysis of CO₂ capture in cement plants: WP4 - Comparative capture process analysis*. Trondheim, 2018 (CEMCAP 641185) [Access on: 24.08.2022]. Available at: <https://zenodo.org/record/2597091#.YwY0hllCRph>

Lena, Edoardo de; Magli, Francesco; Spinelli, Maurizio; Gatti, Manuele; Lindemann Lino, Marco; Hoenig, Volker; Romano, Matteo C. *Comparative analysis of the Oxyfuel and Calcium looping processes for low-carbon cement production*. In: 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15 (Abu Dhabi 15.-18.03.2021). Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3811561

Abanades, Carlos; Cinti, Giovanni; Berstad, David; Hoenig, Volker; Hornberger, Matthias; Jordal, Kristin; Garcia Monteiro, Juliana; Gardarsdottir, Stefania; Ruppert, Johannes; Sutter, Daniel; Meer, Rob van der; Voldsund, Mari. *D2.11 CEMCAP Strategic conclusions – progressing CO₂ capture from cement towards demonstration: WP2 WP Dissemination and exploitation*. 2018 (CEMCAP 641185)

Rodríguez, N.; Alonso, M.; Grasa, G.; Abanades, J.C. *Process for capturing CO₂ arising from the calcination of the CaCO₃ used in cement manufacture*. Environmental Science & Technology. 2008, **42**, pp.6980-6984

Chang, Ming-Hui; Chen, Wei-Cheng; Huang, Ching-Ming; Liu, Wan-Hsia; Chou, Yiang-Chen; Chang, Wen-Chen; Chen, Wang; Cheng, Jui-Yen; Huang, Kuo-En; Hsu, Heng-Wen. *Design and experimental testing of a 1.9MWth calcium looping pilot plant*. Energy Procedia. 2014, **63**, pp.2100-2108. Available at: <https://www.sciencedirect.com/science/article/pii/S1876610214020414>

Dean, Charles; Hills, Thomas; Florin, Nick; Dugwell, Denis; Fennell, Paul S. *Integrating calcium looping CO₂ capture with the manufacture of cement*. Energy Procedia. 2013, **37**, pp.7078-7090

Dean, C.C.; Blamey, J.; Florin, N.H.; Al-Jeboori, M.J.; Fennell, P.S. *The calcium looping cycle for CO₂ capture from power generation, cement manufacture and hydrogen production*. Chemical Engineering Research and Design. 2011, **89**(6), pp.836-855

Romeo, Luis M.; Catalina, David; Lisbona, Pilar; Lara, Yolanda; Martínez, Ana. *Reduction of greenhouse gas emissions by integration of cement plants, power plants, and CO₂ capture systems*. Greenhouse Gases - Science and Technology. 2011, **1**(1), pp.72-82

Romano, Matteo C.; Spinelli, Maurizio; Campanari, Stefano; Consonni, Stefano; Cinti, Giovanni; Marchi, Maurizio; Borgarello, Enrico. *The Calcium looping process for low CO₂ emission cement and power*. Energy Procedia. 2016, **37**(11), pp.7091-7099

Rodriguez, Nuria; Murillo, Ramón; Abanades, J. Carlos. *CO₂ Capture from Cement Plants Using Oxyfired Precalcination and/or Calcium Looping*. Environmental Science & Technology. 2012, **46**(4), pp.2460-2466

Fennell, P.S.; Florin, N.; Napp, T.; Hills, T. *CCS from industrial sources: Technologies, Systems and Policies*. Sustainable technologies, systems and policies: Carbon Capture and Storage Workshop 17. 2012 (Special Issue)

Anthony, Ben. *Ca looping technology: current status, developments and future directions*. Greenhouse Gases - Science and Technology. 2011, **1**(1), pp.36-47

Technology Paper No. 48: Indirect calcination for carbon capture

LEILAC Technology Roadmap 2050 - A cost-effective path to carbon neutral industrial production, 2021. Available at: <https://www.project-leilac.eu/leilac-roadmap-to-2050>

Rennie, Daniel. *Update on the progress of the LEILAC projects*. In: ecra, Ed. Update on Carbon Capture Technology (Online 10.06.2021). Duesseldorf, 2021

LEILAC D2.5 Techno-economics report summary - A cost-effective path to carbon neutral industrial production, 2021. Available at: <https://www.calix.global/wp-content/uploads/2021/10/LEILAC-Techno-economic-Summary-2021.pdf>

Technology Paper No. 48: Post-combustion capture using solid sorbents: Mineral carbonation

Sanna, A.; Uibu, M.; Caramanna, G.; Kuusik, R.; Maroto-Valer, M.M. *A review of mineral carbonation technologies to sequester CO₂*. Chemical Society Reviews. 2014, **43**, pp.8049-8080. Available at: <https://pubs.rsc.org/en/content/articlelanding/2014/cs/c4cs00035h>

Prigiobbe, V.; Hänchen, M.; Werner, M.; Baciocchi, R.; Mazzotti, M. *Mineral carbonation process for CO₂ sequestration*. Energy Procedia. 2009, **1**, pp.4885-4890. Available at: <https://www.sciencedirect.com/science/article/pii/S1876610209009618>

Sipilä, Johan; Teir, Sebastian; Zevenhoven, Ron. *Carbon dioxide sequestration by mineral carbonation: Literature review update 2005–2007*. Turku, 2008. Available at: <http://users.abo.fi/rzevenho/MineralCarbonationLiteratureReview05-07.pdf>

Delgado Torrónategui, Mabell. *Assessing the mineral carbonation science and technology: Master thesis*. Zürich, 2010. Available at: <https://www.research-collection.ethz.ch/handle/20.500.11850/26654>

Mun, Myoungwook; Cho, Heechan. *Mineral carbonation for carbon sequestration with industrial waste*. Energy Procedia. 2013, **37**, pp.6999-7005. Available at: <https://www.sciencedirect.com/science/article/pii/S187661021300876X>

Zevenhoven, Ron; Fagerlund, Johan; Nduagu, Experience; Romão, Inês; Jie, Bu; Highfield, James. *Carbon storage by mineralisation (CSM): Serpentinite rock carbonation via Mg(OH)₂ reaction intermediate without CO₂ pre-separation*. Energy Procedia. 2013, **37**, pp.5945-5954. Available at: <https://www.sciencedirect.com/science/article/pii/S1876610213007649>

Walters, Jerel. *Recovery Act: SkyMine® Beneficial CO₂ Use Project: Final Report; DOE Award Number: DE-FE0002586*. Austin, 2016 (Final DOE Report DE-FE0002586) [Access on: 30.08.2022] Available at: <https://www.osti.gov/servlets/purl/1241314>

Technology Paper No. 49: CO₂ use: Basic chemicals, urea, formic acid, polymers

Álvarez, Andrea; Bansode, Atul; Urakawa, Atsushi; Bavykina, Anastasiya V.; Wezendonk, Tim A.; Makkee, Michiel; Gascon, Jorge; Kapteijn, Freek. *Challenges in the greener production of formates/formic acid, methanol, and DME by heterogeneously catalyzed CO₂ hydrogenation processes*. Chemical Reviews. 2017, **117**(14), pp.9804-9838. Available at: <https://doi.org/10.1021/acs.chemrev.6b00816>

Pérez-Fortes, Mar; Schöneberger, Jan C.; Boulamanti, Aikaterini; Harrison, Gillian; Tzimas, Evangelos. *Formic acid synthesis using CO₂ as raw material: Techno-economic and environmental evaluation and market potential*. International Journal of Hydrogen Energy. 2016, **41**, pp.16444-16462. Available at: <http://dx.doi.org/10.1016/j.ijhydene.2016.05.199>

Otto, Alexander; Grube, Thomas; Schiebahn, Sebastian; Stolten, Detlef. *Closing the loop: Captured CO₂ as a feedstock in the chemical industry*. Energy and Environmental Science. 2015, **8**, pp.3283-3297

Peters, Martina; Köhler, Burkhard; Kuckshinrichs, Wilhelm; Leitner, Walter; Markewitz, Peter; Müller, Thomas E. *Chemical technologies for exploiting and recycling carbon dioxide into the value chain*. ChemSusChem. 2011, **4**(9), pp.1216-1240

Wang, Wei; Wang, Shengping; Ma, Xinbin; Gong, Jinlong. *Recent advances in catalytic hydrogenation of carbon dioxide*. Chemical Society Reviews. 2011, **40**(7), pp.3703-3727

Hendriks, Chris; Noothout, Paul; Zakkour, Paul; Cook, Greg. *Implications of the reuse of captured CO₂ for European climate action policies: Final report*. Utrecht, 2013

Technology Paper No. 50: CO₂ use: Power-to-gas (CH₄)

Götz, Manuel; Lefebvre, Jonathan; Mörs, Friedemann; McDaniel Koch, Amy; Graf, Frank; Bajohr, Siegfried; Reimert, Rainer; Kolb, Thomas. *Renewable Power-to-Gas: A technological and economic review*. Renewable Energy. 2016, **85**, pp.1371-1390

Schaaf, Tanja; Grünig, Jochen; Schuster, Markus R.; Rothenfluth, Tobias; Orth, Andreas. *Methanation of CO₂ - storage of renewable energy in a gas distribution system*. Energy, Sustainability and Society. 2014, **4** (2)

German Energy Agency, dena, Ed. *Power to Gas system solution: Opportunities, challenges and parameters on the way to marketability*. Berlin, 2015

Sternner, Michael; Specht, Michael. *Power-to-Gas and Power-to-X - the history and results of developing a new storage concept*. Energies. 2021, **14**, 6594. Available at: <https://doi.org/10.3390/en14206594>

Gorre, Jachin; Ortloff, Felix; van Leeuwen, Charlotte. *Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage*. Applied Energy. 2019, **253**, 113594. Available at: <https://doi.org/10.1016/j.apenergy.2019.113594>

Baier, Jens; Schneider, Gabriel; Heel, Andre. *A cost estimation for CO₂ reduction and reuse by methanation from cement industry sources in Switzerland*. *Frontiers in Energy Research*. 2018, **6**. Available at: <https://doi.org/10.3389/fenrg.2018.00005>

Technology Paper No. 51: CO₂ use: Power-to-liquids (Methanol)

Liebeck, Miriam; Vogel, G. Herbert. *Ein nachhaltiges Konzept zur Bereitstellung von reinem CO₂ als C-Quelle für Solarfuels - Synergien zwischen Biokohle und Biogas: Herrn Prof. Dr. Werner Weisweiler zum 75. Geburtstag gewidmet*. *Chemie-Ingenieur-Technik*. 1996, **85**(5), pp.618-624

Nguyen, Van Nhu; Blum, Ludger. *Syngas and Synfuels from H₂O and CO₂: Current Status*. *Chemie-Ingenieur-Technik*. 2015, **87**(4), pp.354-375

Verdegaal, Wolfgang Michael; Becker, Sebastian; Olshausen, Christian von. *Power-to-Liquids: Synthetisches Rohöl aus CO₂, Wasser und Sonne*. *Chemie-Ingenieur-Technik*. 2015, **87**(4), pp.340-346

Corcoran, Ronan. *ECRA Project – Report about CO₂ reuse from cement production / MeOH and Methane Synthesis: Technical Report*. Duesseldorf: European Cement Research Academy, ECRA, 2013. Dublin, Univ., Masterthesis, 2013

Gale, John. *Developments in renewable methanol production*, 2016 (IEAGHG information paper 2016-IP4). Available at: https://ieaghg.org/docs/General_Docs/Publications/Information_Papers/2016-IP4.pdf

Nyári, Judit; Magdeldin, Mohamed; Larmi, Martti; Järvinen, Mika; Santasalo-Aarnio, Annukka. *Techno-economic barriers of an industrial-scale methanol CCU-plant*. *Journal of CO₂ Utilization*. 2020, **39**, 101166. Available at: <https://doi.org/10.1016/j.jcou.2020.101166>

International Renewable Energy Agency, Ed. *Innovation Outlook - Renewable Methanol*. Abu Dhabi, 2021. Available at: <https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol>

Technology Paper No. 52: CO₂ use: Enhanced Oil or Gas Recovery (EOR/(EGR))

Heidug, Wolfgang; Lipponen, Juho; McCoy, Sean; Benoit, Philippe. *Storing CO₂ through enhanced oil recovery: Combining EOR with CO₂ storage (EOR+) for profit*. Paris, 2015 (International Energy Agency: Insight Series 2015)

Plasynski, Sean I.; Damiani, Darin. *Carbon sequestration through enhanced oil recovery*. Albany, 2008 (NETL Program Facts Carbon Sequestration 04/2008)

Kokal, Sunil; Al-Kaabi, Abdulaziz. *Enhanced oil recovery: Challenges & opportunities*. World Petroleum Council: Official Publication. 2010, pp.64-69

Technology Paper No. 53: CO₂ use: Algae capture and fuel production, biofuels

The role of algae in carbon capture. In: Wilcox, Jennifer: *Carbon Capture*. New York, 2012, pp.231-243

Sayre, Richard. *Microalgae: The potential for carbon capture*. Bioscience. 2010, **60**(9), pp.722-727

Olofsson, M.; Lindehoff, E.; Frick, B.; Svensson, F.; Legrand, C. *Baltic Sea microalgae transform cement flue gas into valuable biomass*. Algal Research. 2015, **11**, pp.227-233

Theulen, Jan. *Tackling the climate challenge*. World Cement. 2016, (5), pp.109-114

Pond Biofuels launches bioreactor pilot project at St Marys cement plant. Global Cement News. 2014 [Access on: 14.11.2016] Available at: <http://www.globalcement.com/news/item/2680-pond-biofuels-launches-bioreactor-pilot-project-at-st-marys-cement-plant>

Taiwan Cement to expand microalgae production to tackle CO₂. Global Cement News. 2016, [Access on:14.11.2016] Available at: <http://www.globalcement.com/news/item/5102-taiwan-cement-to-expand-microalgae-production-to-tackle-co2>

Technology Paper No. 54: Natural Carbonation

Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; Huang, M.; Leitzell, K.; Lonnoy, E.; Matthews, J.B.; Maycock, T.K.; Waterfield, T.; Yelekci, O.; Yu, R.; Zho, B. *Climate Change 2021 - The physical science basis : Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge; New York, 2021. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FrontMatter.pdf

Andersson, R.; Stripple, H.; Gustafsson, T.; Ljungkrantz, C. *Carbonation as a method to improve climate performance for cement based material*. Cement and Concrete Research. 2019, **124**, 105819. Available at: <https://www.sciencedirect.com/science/article/pii/S0008884619301929>

Standard EN **16757** 2017. *Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements*

Xi, Fengming; Davis, Steven J.; Ciais, Philippe; Crawford-Brown, Douglas; Guan, Dabo; Pade, Claus; Shi, Tiemao; Syddall, Mark; Lv, Jie; Ji, Lanzhu; Bing, Longfei; Wang, Jiaoyue; Wei, Wei; Yang, Keun-Hyeok; Lagerblad, Björn; Galan, Isabel; Andrade, Carmen; Zhang, Ying; Liu, Zhu. *Substantial global carbon uptake by cement carbonation - Letters ; published online 21.November 2016*. Nature geoscience. 2016, **9**, S.880-883. Available at: <http://www.nature.com/ngeo/journal/vaop/ncurrent/full/ngeo2840.html>

Technology Paper No. 55: Enforced (re)carbonation/mineralisation

Zajac, Maciej; Skibsted, Jørgen; Durdzinski, Pawel; Bullerjahn, Frank; Skocek, Jan; Ben Haha, Mohsen. *Kinetics of enforced carbonation of cement paste*. Cement and Concrete Research. 2020, **131**, 106013. Available at: <http://www.sciencedirect.com/science/article/pii/S0008884619312578>

Zajac, Maciej; Skocek, Jan; Durdzinski, Pawel; Bullerjahn, Frank; Skibsted, Jørgen; Ben Haha, Mohsen. *Effect of carbonated cement paste on composite cement hydration and performance*. Cement and Concrete Research. 2020, **134**, 106090

Zajac, Maciej; Skocek, Jan; Skibsted, Jørgen; Ben Haha, Mohsen. *CO₂ mineralization of demolished concrete wastes into a supplementary cementitious material – a new CCU approach for the cement*

industry. RILEM Technical Letters. 2021, (6), pp.53-60. Available at:
<https://doi.org/10.21809/rilemtechlett.2021.141>

El-Hassan, Hilal; Shao, Yixin. *Carbon storage through concrete block carbonation curing*. Journal of Clean Energy Technologies. 2014, **2**(3), pp.287-291

El-Hassan, Hilal; Shao, Yixin. *Early carbonation curing of concrete masonry units with Portland limestone cement*. Cement and Concrete Composites. 2015, **62**, pp.168-177

Shi, Caijun; Wu, Yanzhong. *CO₂ curing of concrete blocks: Research toward greener production*. Concrete International. 2009, **31**(2), pp.39-43

Sereng, M.; Djerbi, A.; Metalssi, O.O.; Dangla, P.; Torrenti, J.-M. *Improvement of recycled aggregates properties by means of CO₂ uptake*. Applied Sciences. 2021, **11**, 6571. Available at:
<https://doi.org/10.3390/app11146571>

Seidemann, Marko; Müller, Anette; Ludwig, Horst-Michael. *Weiterentwicklung der Karbonatisierung von rezyklierten Zuschlägen aus Altbeton (2. Phase: Prozessoptimierung im Labormaßstab und Technologieentwurf): Abschlussbericht über ein Entwicklungsprojekt, gefördert unter dem Az: 23689/02 von der Deutschen Bundesstiftung Umwelt*. Weimar, 2015. Available at: https://www.dbu.de/projekt_23689/02_db_2409.html

8 Annex IV: Definition of TRL (Technology Readiness Level)

The Technology Readiness Level is assessed for application of the technology in cement plants at scale. This is related to a reference plant, which is described in Annex II. Additional detail on the status of the technology and its potential scale is provided in the text of each technology paper.

TRL	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in an operational environment (competitive manufacturing in the case of key enabling technologies; or in space)