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Technical Guidelines on
Energy Efficiency in Major Energy-Consuming Sectors

Energy Efficiency in the Cement Industry

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Imprint

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This report is the second in a series of publications to provide an overview and analysis of energy efficiency measures for key sectors including airports, and the manufacturing industries for pulp and paper, cement, ceramics, and glass fibers, drawing from German and international experiences and best practices.

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Foreword

Dear readers, colleagues and friends,

Despite recent global challenges, we have seen substantial progress being made in the energy transition in Germany and China in the last years. China remains the country with the world's largest installed capacity of renewable energy, whereas in Germany, the share of renewables in the net electricity generation has exceeded 50% for the first time. But whilst the promotion and development of renewable energy plays an important role in our global measures to mitigate the negative impact of climate change, it alone would not be sufficient to protect a liveable future for humanity. To complete the necessary energy transition, it is crucial to improve energy efficiency in order to reduce greenhouse gas emissions in industry, buildings, and transport. Focusing on improving energy efficiency in industrial production is especially powerful, since industry is one of the major energy consuming segments worldwide, making up roughly 29% of total final energy consumption.

As part of its energy transition, the German Federal Government has set itself the target to reach climate-neutrality in all sectors by 2045. By mid-century, Germany aims to cut its primary energy consumption by 50% compared to 2008. To achieve this, Germany adopted the "efficiency first" principle, which aims at prioritising energy efficiency wherever possible.

In a similar vein, China has emphasised energy efficiency as part of its Energy Revolution Strategy (2016– 2030). The 14th Five-Year-Plan set forth by the Chinese government aims to reduce energy intensity by 13.5% and carbon intensity by 18% over the 2021-2025 period. These targets are set against the backdrop of bringing carbon emissions to a peak before 2030 and achieving carbon-neutrality by 2060. To meet these ambitious goals, comprehensive reforms in industries are needed.

The significance of the cement sector for global and Chinese decarbonization efforts cannot be overstated. Not only does cement production account for 8% of worldwide anthropogenic carbon dioxide emissions, but China is also the world's largest cement manufacturer with a production share of more than 50%. It will require coordinated efforts from industry and policy to address the challenges in decarbonizing the cement sector, including improving energy conservation, switching to lower-carbon fuels, reducing the clinker-to-cement ratio and deploying innovative technologies such as carbon capture and storage.

Here, international cooperation between Germany and China can play a contributing role. This report is published as part of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the National Development and Reform Commission (NDRC) and the National Energy Administration of the PRC (NEA), and the project "Supporting Low Carbon Development in Jiangsu Province Phase III" funded by the German Federal Government's International Climate Initiative (IKI).

The report is the second in a series of reports on energy efficiency measures in heavy industry sectors. It highlights process-related measures in the very energy-intensive process of cement production and discusses these according to their implementation potential and effectiveness.

I would like to express my gratitude to all involved experts and implementing partners, especially the National Energy Conservation Center of the PRC (NECC) and the Jiangsu Department for Ecology and Environment, for their ongoing support. I sincerely hope that this study will trigger inspiration and contribute towards finding more energy-efficient solutions that lead us to a cleaner future.

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Abbreviations

AF	Alternative Fuel
BAT	Best Available Technology
BREF	Best Available Technologies Reference Documents
CaO	Calcium Oxide
DS	Dry Solid
EEA	European Environment Agency
ETS	Emissions Trading System
EU	European Union
GBFS	Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GJ	Gigajoule
IEA	International Energy Agency
IGES	Institute for Global Environmental Strategies
IPI	Industrial Production Index
ISO	International Standards Organization
JRC	Joint Research Centre
kWh	Kilowatt hour
MJ	Megajoule
mmWg	Millimetres of Water Gauge (measurement of pressure drop through a medium)
MSW	Municipal Solid Waste
Mt	Million tonne
MWh	Megawatt hour
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
ODEX	Objective of the Energy Efficiency Index
ORC	Organic Rankine Cycle
RDF	Refuse Derived Fuel
SRC	Steam Rankine Cycle
toe	Ton oil equivalent
TFC	Total Final Consumption
UNEP	United Nations Environment Programme
VFD	Variable Frequency Drive
VDZ	Vereinigung Deutscher Zementwerke (Organisation of German Cement Mills)
WHR	Waste Heat Recovery

1

Executive Summary

Energy efficiency improvements in the industrial sector are a powerful and efficient means to reduce overall energy consumption and greenhouse gas emissions given the following facts:

- **Large shares of TFC** (total final energy consumption) **attributable to the industrial sector**, corresponding to 28.6 % (world average) and even 48.3 % (China) (IEA, IEA data and statistics, 2018)
- Prevailing large shares of **fossil fuel in industrial energy consumption** (TCF) – both worldwide (10 % oil products, 20 % natural gas, almost 30 % coal) and in China (roughly 5 % oil products, 7 % natural gas, 50 % coal) (IEA, IEA data and statistics, 2018)
- Considerable leverage effect due **to relatively few actors** in the industrial sector (large energy savings can be achieved by one single industrial company, in contrast to measures targeting other sectors)
- Current potential of considerably high levels of **untapped energy efficiency** and
- **Additional benefits**: increased competitiveness, smoother production, less down time, positive impacts on efficiency covering all resources: water, air, soil and materials.

In Europe, the most successful range of measures for energy efficiency improvement comprises the application of benchmark values, both for the permission of new installations (see also Best Available Technologies as referred to in the **BAT documents**), and the determination of reference values for the share of free allocation in the **European Emission Trading Scheme**. The EU ETS is a cap-and-trade system in place since 2005. It currently covers about 11,000 heavy energy users including power stations, industrial plants and airlines, together responsible for about 40 % of overall carbon emissions in the participating countries. Preliminary results show that so far, the scheme has significantly contributed to overall emission reductions and led to reductions by approximately 35 % in the period 2005 - 2019. Further efforts are required to reach the overall goal of GHG reduction by 55 % by 2030, as defined in the European Green Deal. Another important policy instrument which leads to continuous improvement of (industrial) processes is the obligation of large enterprises to perform external energy audits every four years or alternatively implement an energy or environmental management system following the requirements of the **Energy Efficiency Directive** (Directive 202/27/EU and its amendment in 2018).

Energy efficiency measures range from “simple” good housekeeping and the use of control systems (both of which are prerequisites for the following measures) to equipment change, process integration and application of alternative processes. The following guideline focuses on process-related measures for the **cement industry**. The selection of these measures is based on their achievable potential/applicability (with focus on China) as well as their effectiveness (necessary changes/investment costs in comparison to achievable benefit). Data sources include not only international and local studies/analysis but also estimations based on experts’ experiences.

Unit energy consumption per tonne of cement in Europe ranges from 0.7 MWh to 1.5 MWh, which still shows some room for improvement at individual mill level. However, the overall average figure has remained almost stable in the last years, amounting to about 1MWh/tcement. The unit energy consumption level is influenced by various factors, including the clinker-to-cement ratio (percentage of clinker compared to other non-clinker components) and the energy efficiency of the production process. Therefore, the use of other materials in cement and the reduction of the clinker-to-cement ratio plays an important role in lowering emissions and energy consumption. Ordinary Portland cement can contain up to 95% clinker (the other 5% being gypsum). Typical clinker ratios in European countries are around 60-80% (with some exceptions).

Considering that the major share of overall energy consumption is attributable to thermal energy (about 88%) in clinker making as opposed to electricity consumption in other processes, this guideline covers both the clinker making and the cement production, including raw material preparation and grinding, clinker making, clinker cooling and finish grinding. Emphasis will be on clinker making as the most energy-intensive sub-process. The guideline will also examine other relevant topics including energy supply options (switching to lower-carbon fuels) and alternative raw materials (reducing clinker-to-cement ratios).

The following energy efficiency measures were identified as the most promising ones and are described in detail in this guideline.

Table 1: Overview Measures

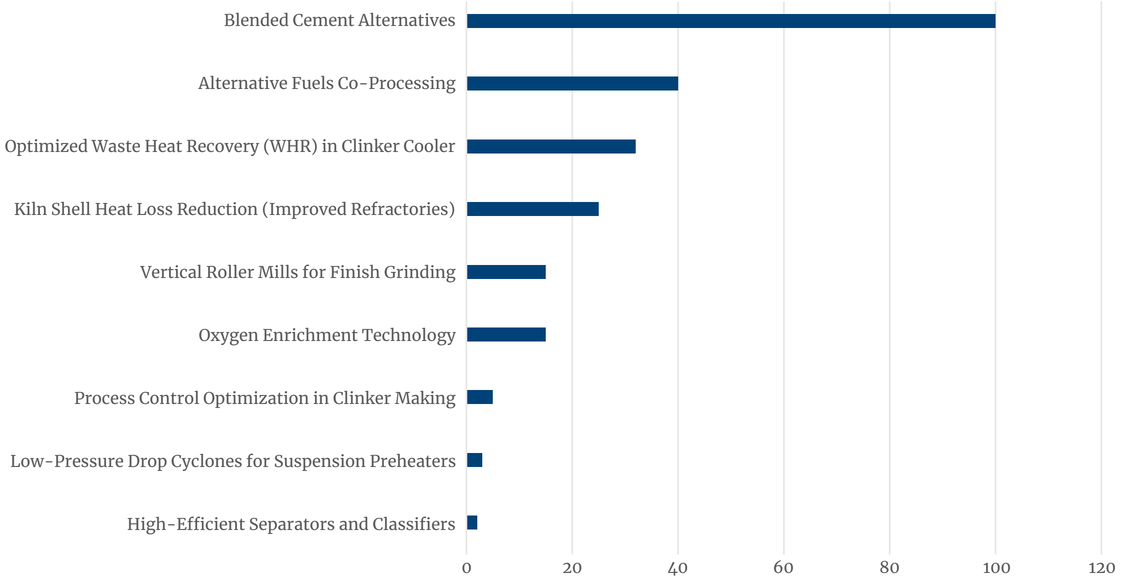
Chapter	Measure	Process
4.1	High Efficiency Separators and Classifiers	Raw Material Preparation/Finish Grinding
4.2	Blended Cement Alternatives	Raw Material Preparation
4.3	Alternative Fuels Co-Processing	Fuel Preparation
4.4	Process Control Optimization in Clinker Making	Clinker Making
4.5	Kiln Shell Heat Loss Reduction (Improved Refractories)	Clinker Making
4.6	Low-Pressure Drop Cyclones for Suspension Preheaters	Clinker Making
4.7	Oxygen Enrichment Technology	Clinker Making
4.8	Optimized Waste Heat Recovery (WHR) in Clinker Cooler	Clinker Cooling
4.9	Vertical Roller Mills for Finish Grinding	Finish Grinding

Evaluating energy efficiency potentials through final energy consumption (electricity and thermal energy) must always be seen in close connection with relevance to GHG reduction. This means the actual GHG reduction impact strongly depends on the actual fuel replaced and the energy source used for electricity production.

Largest leverage effects can be achieved by switching to Blended Cement Alternatives which have considerably lower process emissions than standard (Portland) cement and by substituting fossil fuels (Alternative Fuels Co-Processing). Clinker making is the most energy-intensive process step and should be optimized (see chapters 4.4- 4.7). Despite the relatively low share of electricity consumption compared to thermal energy consumption, we further recommend using established energy-efficient grinding and separating technologies.

The actual investment costs and savings depend on the current type and energy consumption status of the respective plant, but in light of respective literature and own experiences, the following CO2 emission reduction potentials are identified[1]:

Figure 1: Saving Potentials of Selected Measures (kg CO_2/t product)



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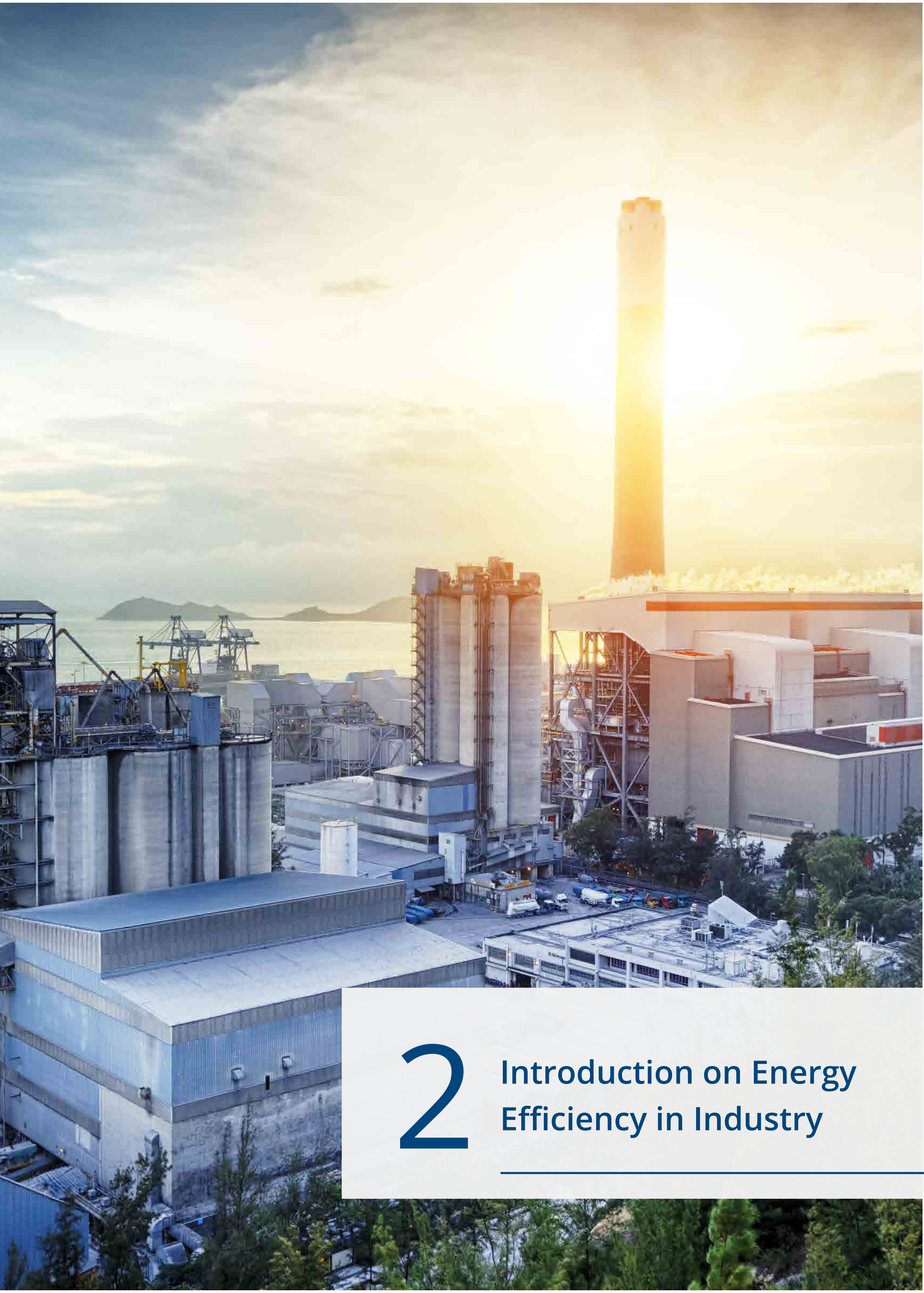
[1] Depending on the type of measure/where the measure takes place this either refers to clinker or to cement. “Product” is used as the umbrella term for both.

Table 2: Energy and CO2 Savings Overview

Chapter	Measure	Energy Savings				CO_2 Mitigation	
		Thermal	Electrical	Value	Unit	Value	Unit
4.1	High Efficiency Separators and Classifiers	-	x	2.2 -4.5	kWh/$t_{product}$	1.1-2.3	kg CO_2/$t_{product}$
4.2	Blended Cement Alternatives	x	(x +)	30-110	kWh/$t_{clinker}$	100	kg CO_2/$t_{clinker}$
4.3	Alternative Fuels Co-Processing	(x +)	(x +)	Final Energy consumption increases, however CO_2 emissions (and primary energy consumption) are reduced		30-50	kg CO_2/$t_{clinker}$
4.4	Process Control Optimization in Clinker Making	x	x	32	kWh/$t_{clinker}$	2.9-5.9	kg CO_2/$t_{clinker}$
4.5	Kiln Shell Heat Loss Reduction (Improved Refractories)	x	-	33-111	kWh/$t_{clinker}$	25	kg CO_2/$t_{clinker}$
4.6	Low-Pressure Drop Cyclones for Suspension Preheaters	x	x	3.6-4.4	kWh/$t_{clinker}$	2-3	kg CO_2/$t_{clinker}$
4.7	Oxygen Enrichment Technology	x	-	27-55	kWh/$t_{clinker}$	10-20	kg CO_2/$t_{clinker}$
4.8	Optimized Waste Heat Recovery (WHR) in Clinker Cooler	x	x	Strongly depends on the plant and WHR system size.		32	kg CO_2/$t_{clinker}$
4.9	Vertical Roller Mills for Finish Grinding	-	x	10-15	kWh/t_{cement}	8-19	kg CO_2/t_{cement}

(x +). value increases

Energy (and resource) saving potentials which go beyond currently applied energy saving measures can be realized by further changing the clinker-cement- factor and by using technologies of carbon capture and storage.



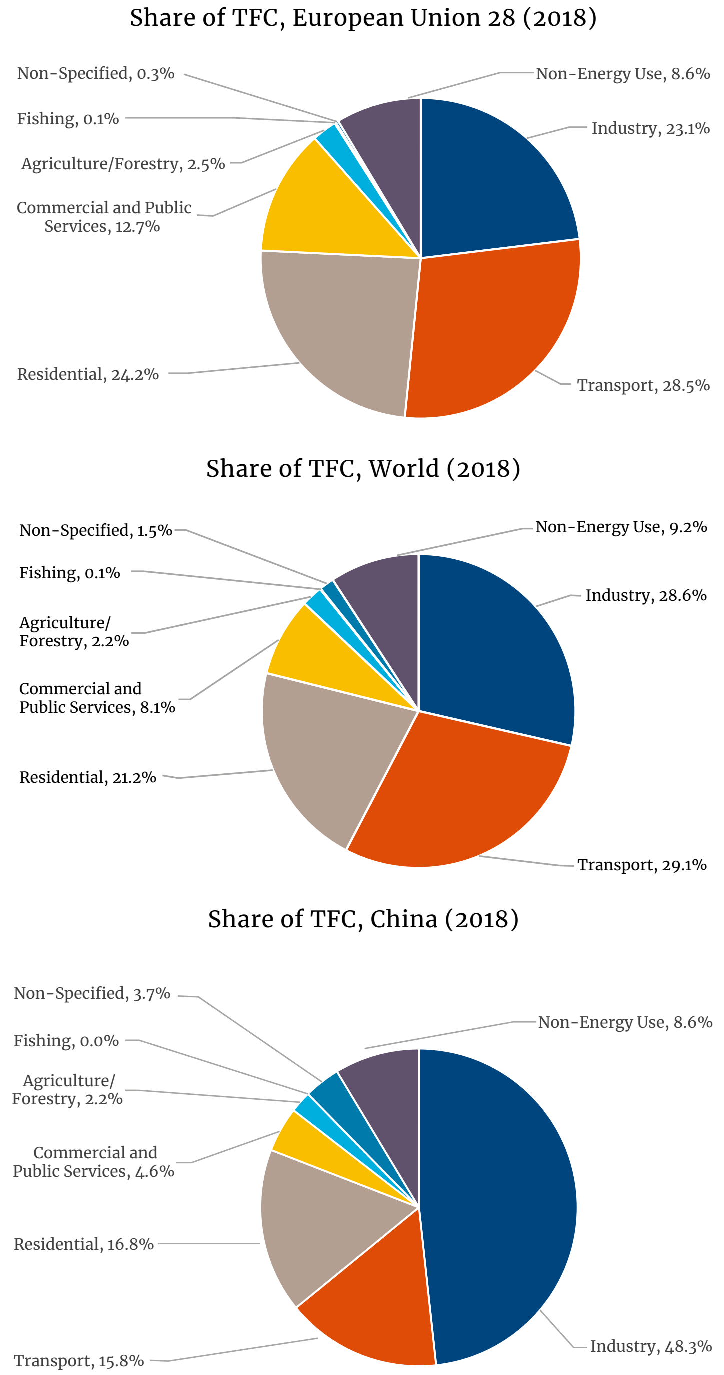
2

Introduction on Energy Efficiency in Industry

2.1 Energy Consumption and Status of Energy Efficiency

Industry is one of the **major energy consuming sectors** worldwide as well as in China. This is shown in the following charts depicting the Total Final Consumption (=TFC) shares:

Figure 2: TFC Shares



Share of TFC, European Union 28 (2018)

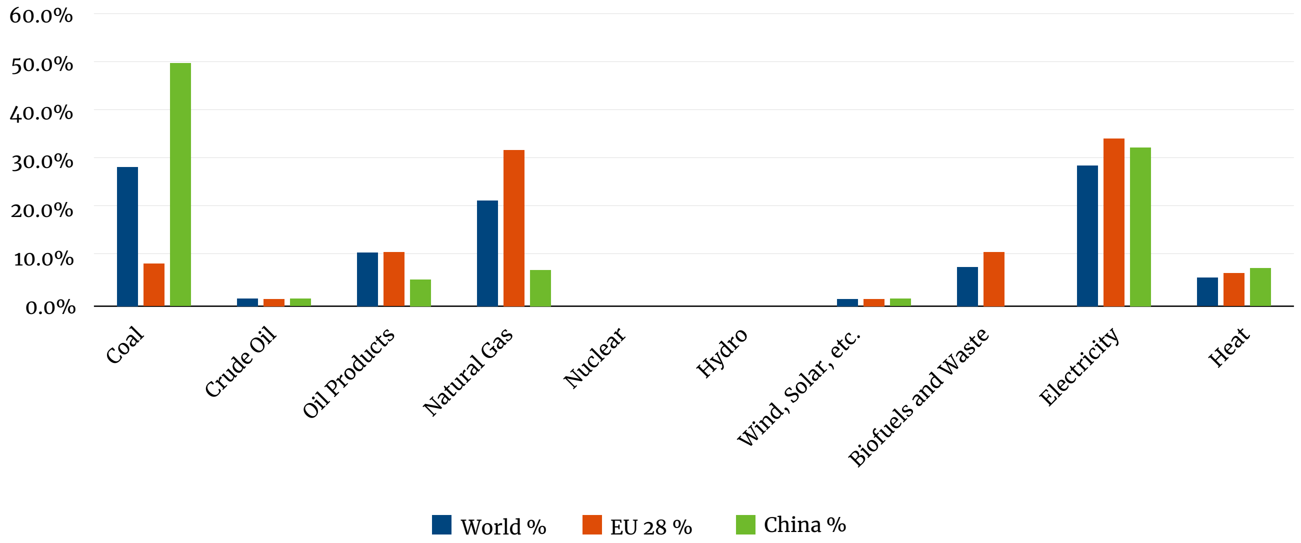
Share of TFC, World (2018)

Share of TFC, China (2018)

Source: (IEA, IEA data and statistics, 2018)

Regarding energy sources used in industry, the relative importance of different energy sources varies considerably among countries - especially with respect to coal and natural gas.

Figure 3: TFC Shares / Industry,



Source: (IEA, IEA data and statistics, 2018)

Energy efficiency in industry is considered to be one of the most powerful measures to reduce overall energy consumption and GHG –not only due to the size and importance of the industrial sector, but also because there are relatively few actors in comparison to others sectors. Thus, efficiency changes in one plant leads to comparatively large savings.

In the European Union, industrial energy consumption has been decreasing considerably since 2007. However, more than half of the reduction was due to a decrease in the overall industrial activity caused by the recession. **Energy efficiency has improved in the last years** (at rates at about 1 % per year), but is still at a lower level than in the early 2000s. This can be partly explained by large equipment not operating at full capacity – and thus less efficiently – as well as by the fact that part of energy consumption is relatively fixed and not related to production levels. (Fraunhofer ISI, 2018)

Overall energy efficiency progress can be measured via different indicators. One of them is the ODEX indicator[2] which measures energy consumption (physical, not financial) by production activity at sector level. This indicator is used for different industrial sub-sectors in the European Union and shown in the following graph.

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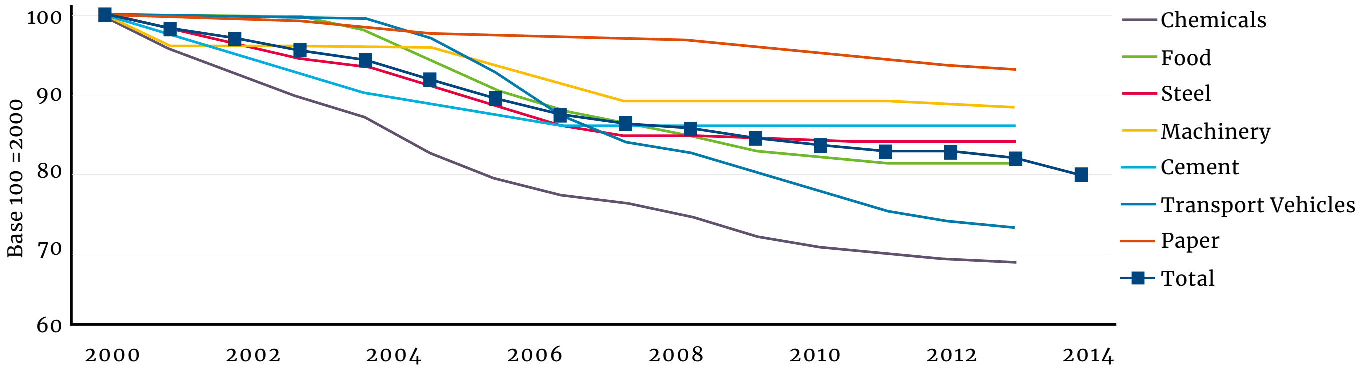
[2] "ODEX" (objective of the energy efficiency index) is derived at sector level (household, industry, transport) and weighs the indices of specific consumption by sub-sector (or end-use) with the share of each sub-sector in the sector's energy consumption. In the industry sector ODEX is derived at the level of 14 branches based on specific consumption per tonne for steel, cement and paper and consumption per IPI (industrial production index) for other branches.

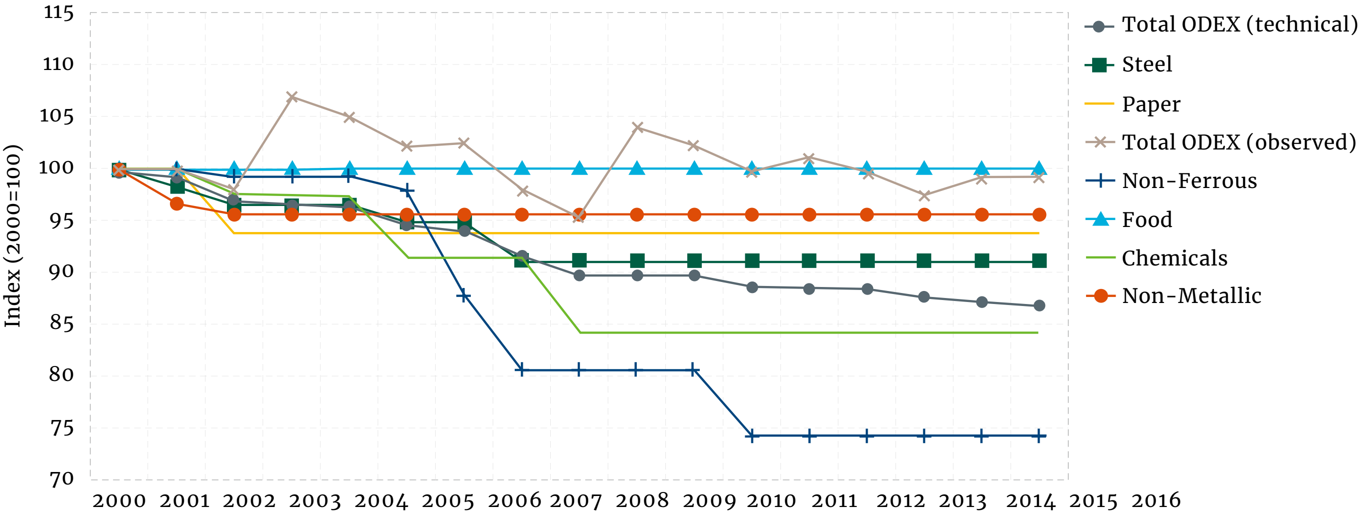
Figure 4: ODEX Indicator- Industrial Sectors European Union



Source: (Bruno Lapillonne, 2018)

It is clear that the overall energy efficiency has been improving by about 1.4 % per year since 2000 (or by 17 % cumulatively since 2000). However, the rate of improvement slowed down since the economic crisis. In Germany, for example, this effect is more noticeable:

Figure 5: ODEX Indicator- Industrial Sectors Germany



Source: (Fraunhofer ISI, 2018)

There are several studies referring to **considerable potential of energy efficiency currently available worldwide.** E.g., a study from IEA (2007) cited in the UNEP Best Practices and Case Studies Analysis (Fawkes, 2016) shows an overall potential summing up to 600-900 Mtoe/year and 1,900–3,200 Mt CO2 savings per year based on commercial, cost-effective proven technologies. These figures correspond to global improvement potentials of around 18 - 26 % of global industrial energy uses and 19 – 32 % of global CO2 emissions in the industrial sector. The highest potentials are expected to be in the chemicals, iron and steel, cement and pulp and paper sectors.

2.2 Energy Efficiency Policy and Management

In general, policy options can be categorized into “carrots” (incentives which make the desired action more attractive, in this case increasing energy efficiency) and “**sticks**” (penalties for companies not complying with relevant targets). These policy options can take the form of regulatory measures, fiscal/financial policies and information/capacity building (Fawkes, 2016). In the industrial sector in Europe, the most important tools and measures are the definition of benchmarks (Best Available Technologies), the European Emission Trading scheme and the obligation to apply energy auditing.

There are different energy consumption/energy efficiency figures in the same industry’s different production sites, depending on the applied technologies, the size of the plant and its operation. One of the most powerful method of examining different production sites is to compare their actual consumption with sectoral energy benchmarks and – more globally – their respective distance to **Best Available Technologies (BAT).**

In Europe, for example, there are reference documents describing Best Available Technologies for industrial sub-sectors, called BREFs, which follow the requirements of the EU Industrial Emission Directive[3]. The results cover not only the energy consumption performance, but also the relevance for emissions to air, water and soil as well as resource efficiency. They are derived from discussions between industry representatives, NGOs, the EU member states and the European Commission and are published on the website of the European IPPC Bureau under https://eippcb.jrc.ec.europa.eu/reference. According to these results, new installations have to comply with BAT standard and corresponding emission levels from the start of operation. Existing installations have to be adapted within 4 years after publication of BAT conclusions.

Another application of benchmarking against the most efficient industrial plants can be found within the **European Union Emission Trading scheme**, which has been operating since 2005. Designed as a cap-and-trade system, this market-based mechanism aims to reduce overall GHG emission in the most cost-effective way. This means that a specific cap is defined for all covered installations (currently about 11,000 heavy energy-using installations including power stations & industrial plants and airlines operating between these countries) which together are responsible for about 40 % of overall emissions of the participating countries[4]. This cap defines the total amount of greenhouse gases which can be emitted by all installations covered by the system. The “emission allowances” have to be surrendered each year by the companies to fully cover their actual emissions. Some of the allowances are allocated to companies via a mechanism that takes into account historical emissions of the respective sector and emission levels of the best 10% of participating companies (benchmarking), amongst other factors. The difference (either surplus or lack) can be traded on the market.

Preliminary results show that the scheme reaches its targets. Emissions of the **covered installations were reduced by about 35 % between 2005 and 2019**. In order to achieve a higher and more robust carbon price, the “Market Stability Reserve” was introduced in 2019. Following the **European Green Deal**[5], the EU’s targets overall greenhouse gas emission **reduction of 55 % by 2030**. Within this package, energy efficiency was the first to be identified as one of the key objectives because it was considered one of the easiest ways to reduce greenhouse gas emissions and reduce energy costs. Thus, the EU has set binding targets of at least **32.5 % increase in energy efficiency by 2030**, relative to a ‘business as usual’ scenario. Additionally, the new target for **renewable energy share** was set to at least **32 %** for 2030 (European Commission, 2018, last update 12/2020). In this regard, a revision and possible expansion of the EU-ETS is currently under discussion.

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[3] Industrial Emissions Directive (IED, 2010/75/EU)

[4] Countries of the European Union, Norway, Iceland

[5] Following the 2015 Paris Climate Agreement, the European Union pledged to achieve greenhouse gas emission reductions of at least 40% by 2030 compared to 1990. With a view to this target and in order to pave the way towards energy transition the European Commission presented new, more ambitious rules in 2016, called the Clean Energy Package for all Europeans.

What is important for any saving project is the **application of monitoring and verification**, as this sets the basis of verifying the actually achieved savings. For those companies wishing to extend their knowledge basis and integrate energy management in their overall quality/environmental processes, the application of established management tools and processes in the Standard ISO 50001 can be an option.

In Europe, large enterprises either have to apply such energy (or environmental) management systems or regularly conduct energy audits in every four years following the requirements of the **Energy Efficiency Directive** (Directive 2012/27/EU and its amendment in 2018).[6]

2.3 Overview of Energy Efficiency Measures

Reaching (theoretical) energy efficiency limits set by the rules of thermodynamics is not expected, but there are still other limitations, especially due to ongoing practice and cost constraints. The more "low hanging fruits" are harvested, the more difficult it gets to identify further feasible energy saving potentials. In the "**energy maturity model**" (cited in: (Fawkes et al., 2016) it is differentiated between:

- **(Good) housekeeping:** including maintenance, routine inspections, correct installation of all equipment, correct size of equipment according to actual demand, ensure proper insulation etc.
- **Use of control systems:** covering e. g. temperature control limits, reducing excess flows, using variable speed drives, using preventive maintenance
- **Simple modification:** change of equipment
- **Process integration:** using heat exchangers, closed-loop systems or waste heat recovery and
- **Alternative processes:** such as combined heat and power plants, applying dynamic simulation and predictive controls, or applying new process technologies

The higher the energy maturity, the higher the potential savings, but the associated efforts, knowledge, complexity and business risks also increase. Thus, all saving projects should begin with easy and low energy maturity aspects. Improving single cross-cutting technologies such as motors, variable speed drives and their optimization are important for several industrial sectors, but these are not within the scope of this guideline. The same applies to the need of considering the impact of the status of industrial enterprises' buildings on the energy consumption. Process-related measures along the whole production process might be viable options for different industries and are explained in the industry-specific guidelines. (Fawkes, 2016) These measures can include:

- The **optimization of steam systems** (minimize the number of heat transformations, preheating water or air, using energy efficient heat exchanger designs, minimizing/optimizing simultaneous heating and cooling)
- Optimization of **cooling and refrigeration**
- Recognizing the effects of **water chemistry** (mineral salts, dissolved gases etc.) on water quality/treatment requirements
- Installing **combined heat and power** instead of high-temperature heat losses
- Applying **heat recovery** both within one company or also to neighboring heat users or district heating systems
- Using **waste heat to power** for industrial processes with high waste heat temperatures
- Converting waste from production as an **energy source** (after screening options for re-use or recycling)

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[6] Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance.)

3

Overview of the Cement Sector

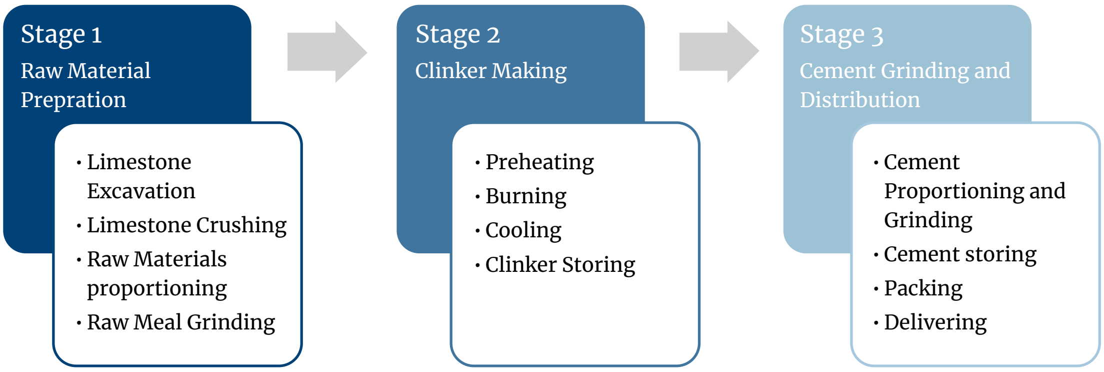
This chapter provides an introduction to overall production processes in the cement sector and their relevance to overall energy consumption. It also gives a statistical overview of production and energy consumption related figures in Europe.

3.1 Description of the Production Process and Process Steps

The single most widely used human-made material on the planet is cement, with nearly 521 kilograms of cement consumed per capita every year (CemNet, 2018).

The following diagram illustrates the different stages of the cement production process.

Figure 6: Production Stages of Cement in Different Methods



The most important raw materials for producing cement are marl, a calcium carbonate or lime-rich mud, and limestone. Calcium oxide (CaO) from limestone, chalk, shells, shale, or calcareous rock is responsible for the strength of the cement.

Calcium oxide (CaO) plays an essential role during the mineralization process. If lime content is lower than required minimum level, the required strength of cement will reduce, and the mineralization process time will increase. Silica, as a second essential ingredient, can be obtained from sand, argillaceous rock, etc. Adding sufficient silica helps to form di-calcium and tri-calcium silicates, which imparts strength to the cement (Estrela, Sousa-Neto, & Guedes, 2012).

The cement manufacturing process has undergone many changes over the past decades. There are four different methods of cement production: wet kiln method, semi-wet kiln method, semi-dry kiln method, and dry kiln method. In 2007, the large majority (90%) of Europe's cement production was from dry process kilns. A further 7.5% of output was from semi-dry and semi-wet process kilns, and only about 2.5% from wet process kilns (Institute for Prospective Technological Studies, 2013).

The **wet process** is typically preferred whenever the raw material has a moisture content of more than 20% by weight. The clay is mixed with water while crushing and it is further mixed with limestone and other ingredients into a slurry of high concentration. In order to decrease kiln fuel consumption, water addition is controlled during raw material grinding. This way, the amount of water used is at a minimum but the slurry still meets the required flow and pumpability characteristics (32% to 40% water). Wet processes are more energy-consuming and, thus, more expensive (Institute for Prospective Technological Studies, 2013).

In the **semi-wet method**, materials coming out from the mill are like slurry material. Before entering the kiln, these materials are filtered by pressing and fed into the kiln in cubiform. Factories using semi-dry processes are likely to move on to dry method whenever an upgrade or significant improvement is required. Plants using wet or semi-wet methods usually have access only to moist raw materials, as it is the situation in Denmark and Belgium.

All above-mentioned methods include the following processes:

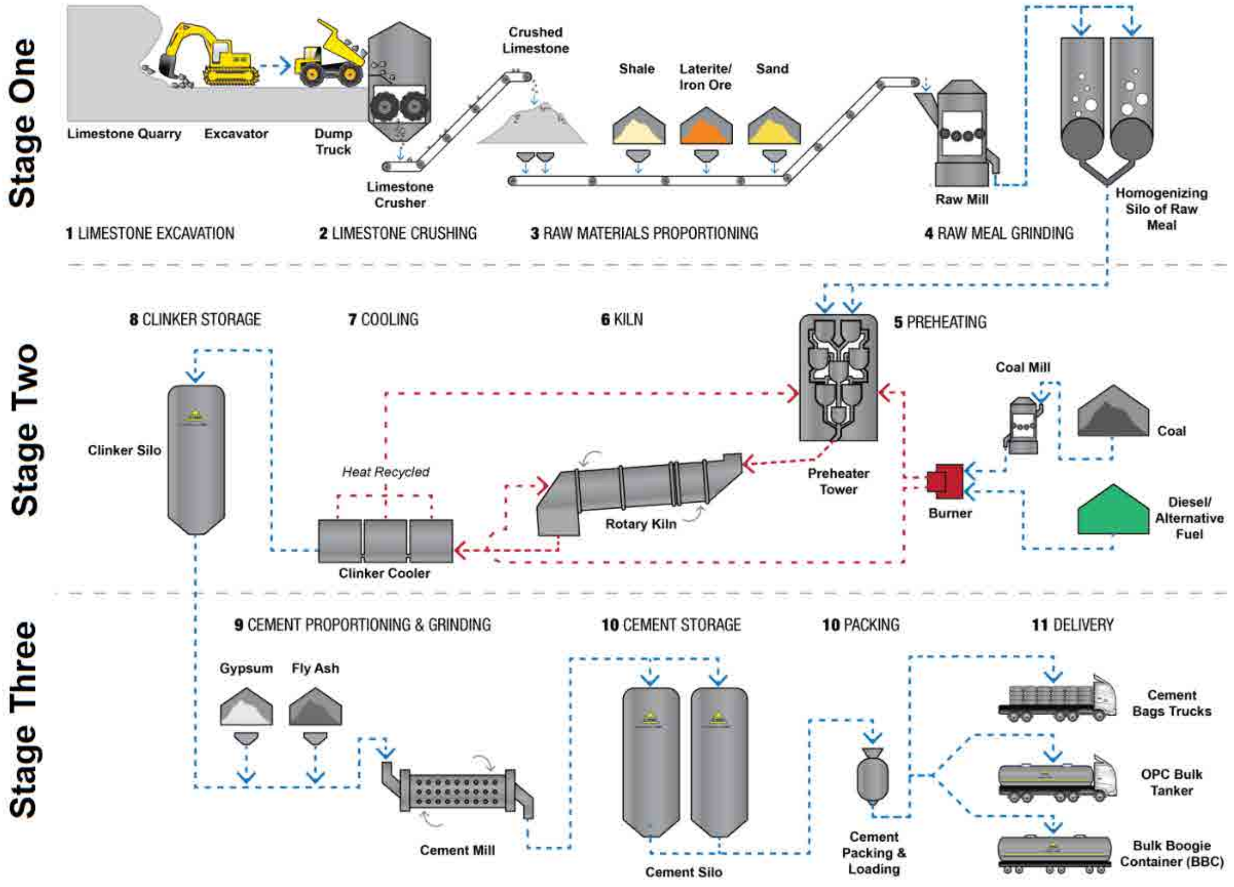
- Raw materials – storage and preparation
- Fuels – storage and preparation
- Clinker making
- Clinker cooling
- Cement–preparation and storage (finish grinding)
- Packaging and dispatch

The **dry process** can be explained in three stages (Figure 7):

Stage 1 - Raw Material Preparation

In stage 1 (**raw material preparation**) the necessary raw material such as calcium carbonate, silico, alumina, and iron from limestone rock chalk and clay or shale is extracted. After the limestone crusher, the raw materials are mixed and grinded. The resulting product is called "raw meal" and it usually contains more than 70% $CaCO_3$. The remaining compositions are SiO_2, Fe_2O_3, Al_2O_3, K, and Cl.

Figure 7: Cement Production Process in Dry Method



Source: (World Business Council for Sustainable Development, 2015)

Depending on the quality of the quarry, the composition of the raw material can vary. Raw materials have to meet certain characteristics, composition of chemical elements, and components that are necessary for cement production. The following table shows average consumptions of raw materials for the production of cement in the European Union (EU):

Table 3: Average Raw Material Consumption for Cement and Clinker Production in the EU Countries

Materials (Dry basis)	Per Tonne Clinker	Per Tonne Cement	Per Year Per Mt Cliker
Limestone, clay, shale, marl, other	1.57 t	1.27 t	1568000 t
Gypsum, anhydrite	-	0.05 t	61000 t
Mineral additions	-	0.14 t	172000 t

Source: (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013)

In addition to the main components, these raw materials also contain some metals as listed in the table below:

Table 4: Metals Content in Raw Materials and Raw Meal of Cement Production in the EU Countries

Elements		Clay and Argillite	Limestone, Marl and Chalk	Raw Meal
		mg/kg DS(')		
Antimony	Sb	No data available	1-3	<3
Arsenic	As	13-23	0.2-20	1-20
Beryllium	Be	2-4	0.05-2	0.1-2.5
Lead	Pb	10-40	0.3-21	4-25
Cadmium	Cd	0.02-0.3	0.04-0.7	0.04-1
Chromium	Cr	20-109	1.2-21	10-40
Cobalt	Co	10-20	0.5-5	3-10
Copper	Cu	No data available	3-12	6-60
Manganese	Mn	No data available	≤250	100-360
Nickel	Ni	11-70	1.5-21	10-35
Mercury	Hg	0.02-0.15	<0.01-0.13	0.01-0.5
Selenium	Se	No data available	1-10	<10
Tellurium	Te	No data available	<4	<4
Thallium	Tl	0.7-1.6	0.05-1.6	0.11-3
Vanadium	V	98-170	4-80	20-102
Tin	Sn	No data available	<1-5	<10
Zinc	Zn	59-115	10-40	20-47
(') DS: Dry Substance.				

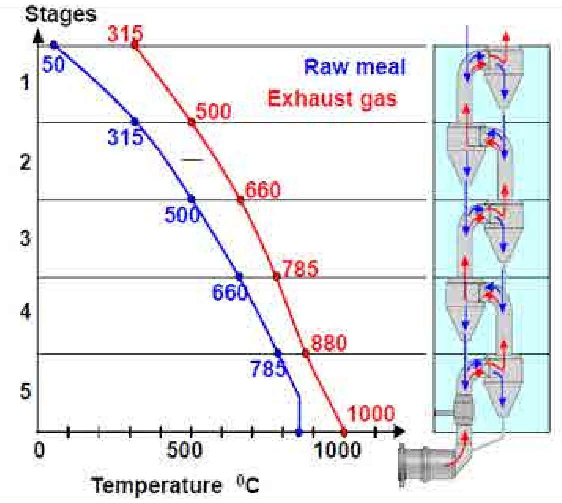
Source: (VDI-Richtlinien, 2003)

Stage 2 – Clinker Making and Cooling

After the raw meal crushing and homogenizing, the raw meal goes through **stage 2 – clinker making and cooling** (Figure 7). The raw meal has 3-5 % moisture content and this content needs to evaporate before entering the kiln. After stage 1, the raw meal is introduced at the inlet gas duct at stage 2 (**preheating**). The gas temperature in the preheating section is between 300 °C to 900 °C. Typically the preheating section consists of 4-6 cyclones. The temperature profile of the raw meal and gas in the cyclones is shown in the figure below. As it is shown, the raw meal has a temperature of lower than 50 °C at entering to the first cyclone. After being in direct touch with the hot flue gas and thermal energy exchange, the temperature of the material increases to almost 850 °C (Hidayat, 2013).

It is important to control the material temperatures during drying. As the limestone dissociates at approx. 800 °C, heating during the drying process, which occurs before entering the last cyclone, should not cause any chemical changes in the raw meal. The decomposition of calcium carbonate (limestone) to calcium oxide (lime) reaction is called calcination. The calcination is an endothermic reaction. Depending on kiln and cyclones construction, calcination happens either before raw material enters the kiln or at the beginning of the kiln.

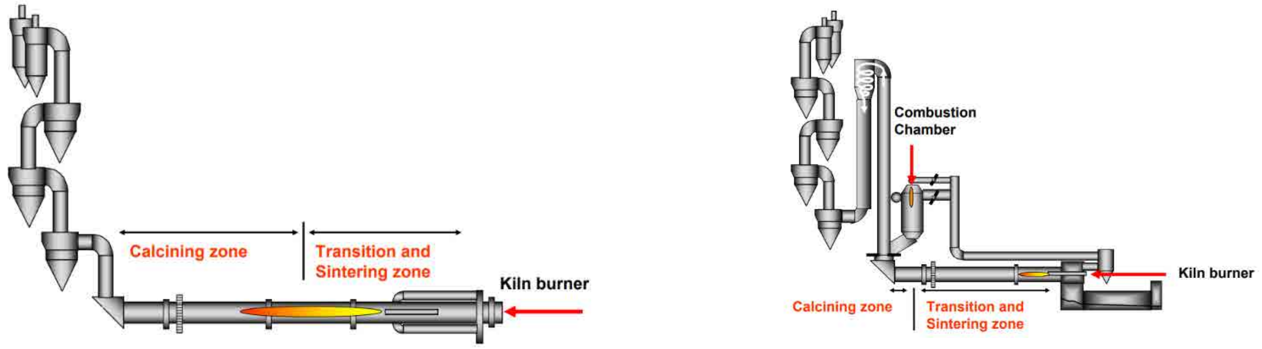
Figure 8: Temperature Profile of Raw Meal and Exhaust Gas in Cyclones



Source: (Hidayat, 2013)

Kilns with **preheater and pre-calciner** have been available to the cement industry since the 1970s. In this technology, the thermal energy is introduced in two points, in the kiln burning zone, known as the main burner, and in the combustion chamber between the preheater and the rotary kiln. Due to the longer retention time of the hot meal in the pre-calcination zone, 65% of the total fuel is used in the chamber. The raw meal is almost entirely calcined when it enters the kiln (90% and higher calcination rate). The following illustrations show the construction differences between kiln with and without pre-calciner. Characteristics of each system are mentioned in Table 5.

Figure 9: Kiln System without Pre-Calciner (Left), Kiln System with Pre-Calciner and Combustion Chamber (Right)



Source: (Hand, 2007)

Table 5: Kiln System Characteristics

Kiln System	Characteristics
Kiln System without Pre-Calciner	● Low pre-calcination rate of the hot meal (app. 40%) ● High fuel used for sintering and calcination in the kiln
Kiln System with Pre-Calciner and Combustion Chamber	● High pre-calcination rate of the hot meal (> 90%) ● Fuel energy in the calciner (up to 50%) is used for pre-calcination ● Fuel energy in the kiln is used for sintering process ● Allows utilization of secondary fuels with low-quality properties in the combustion chamber

In order to convert the raw material-mix to cement clinker, high process temperature is required in the burning zone. It is essential to maintain kiln charge temperatures in the sintering zone of the rotary kilns at 1400 °C - 1500 °C, and the flame temperature at about 2000 °C. Clinker, as an end product of the kiln, is cooled down within coolers and stored in silos.

Stage 3 – Finish Grinding

At stage 3 (Figure 7) – **finish grinding** (and further steps), gypsum and fly ash is added to the clinker produced in stage 2. After crushing and grinding the input materials, the cement is stored, packed, and made ready for delivery.

Depending on the type of fuel used (traditionally coal or fossil fuels, nowadays increasingly alternative fuels), additional process steps are required for **fuel preparation**. For details, refer to chapter 4.3.

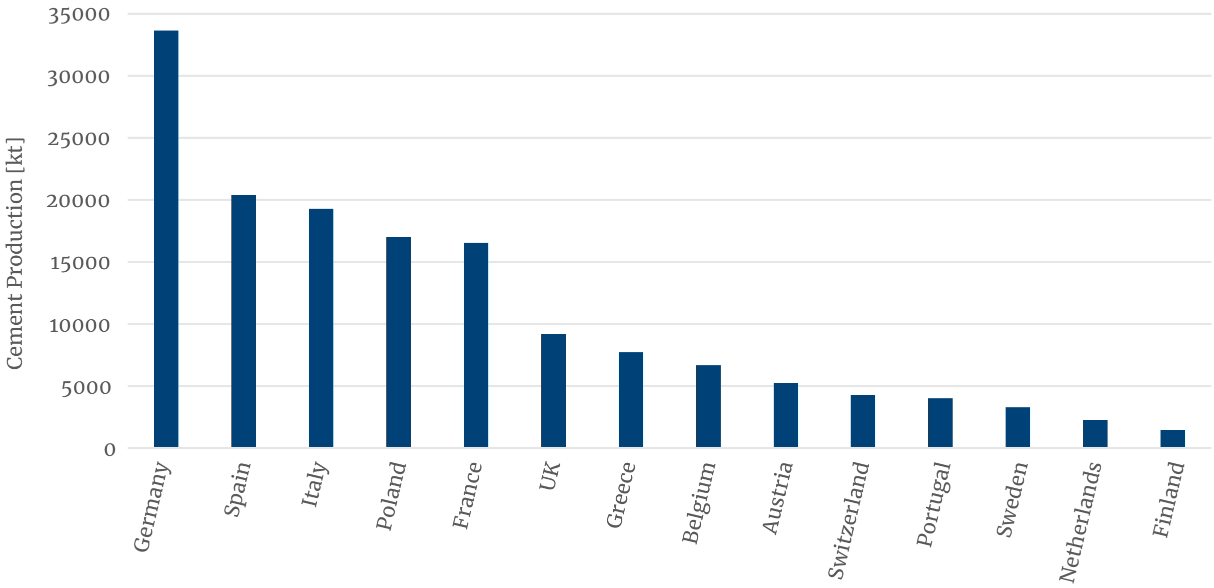
3.2 Current Situation and Development of Energy Efficiency in the Sector

This section analyses the current situation of energy consumption and energy efficiency of the cement sector in Europe and provides an overview of the major energy consuming processes relevant for this sector.

3.2.1 Energy Statistics and Benchmarks for the European and German Cement Industry

The chart below provides an overview of cement production in European countries. The aggregated amount of cement production in the European Union (EU 28) was 167.018 kt in 2018. The largest four production countries (Germany, Spain, Italy, Poland, France) covered 56% of overall production.

Figure 10: Cement Production Figures in Europe

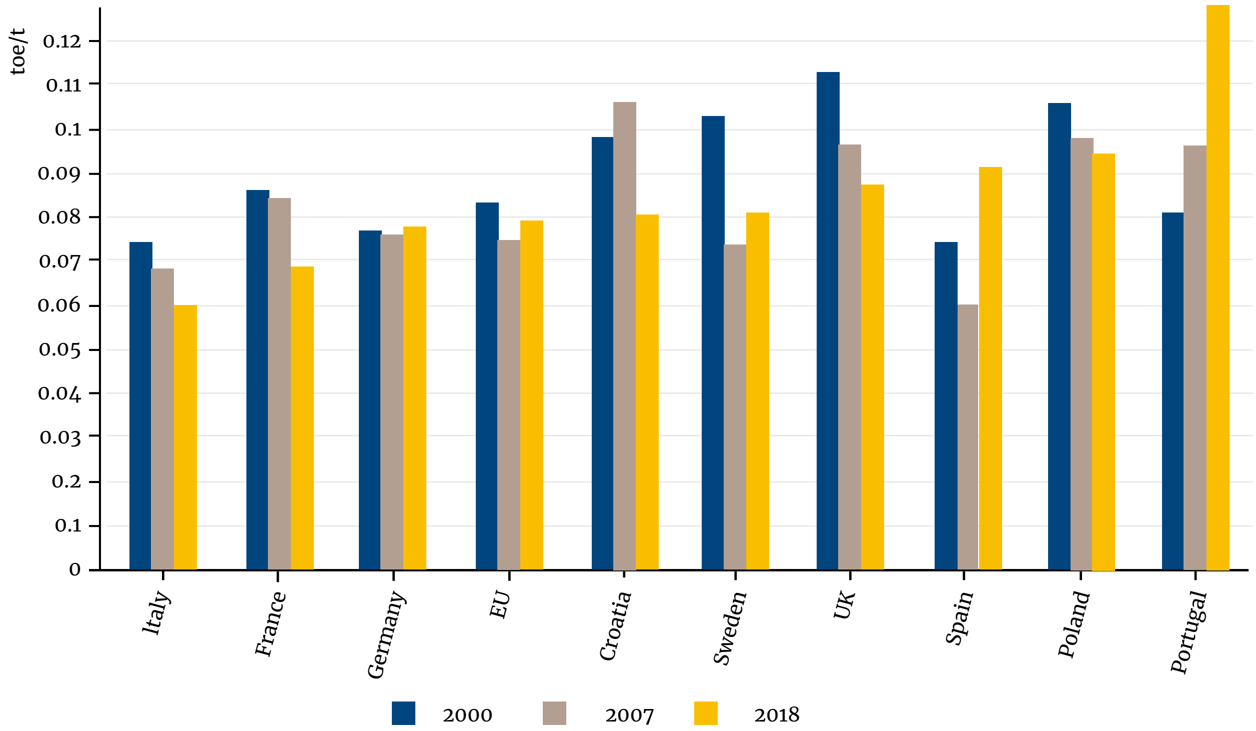


Source: (ODYSSEE Database, 2018)

In 2020, 54 cement mills have been operating in Germany, 33 of which also include clinker making. (VDZ, 2021)

Unit energy consumption is defined as the energy input necessary for the production of one unit of output. In the case of cement production, to the relevant unit is "one tonne cement produced". In 2018, **unit energy consumption** in toe/tcement ranged from 0.06 toe/t (Italy) to 0.13 toe/t (Portugal) whereas European Union average corresponded to 0.08 toe/t (**approximately 1 MWh**/tonne).

Figure 11: Unit Consumption toe/t $_{\text{Cement}}$ in Europe



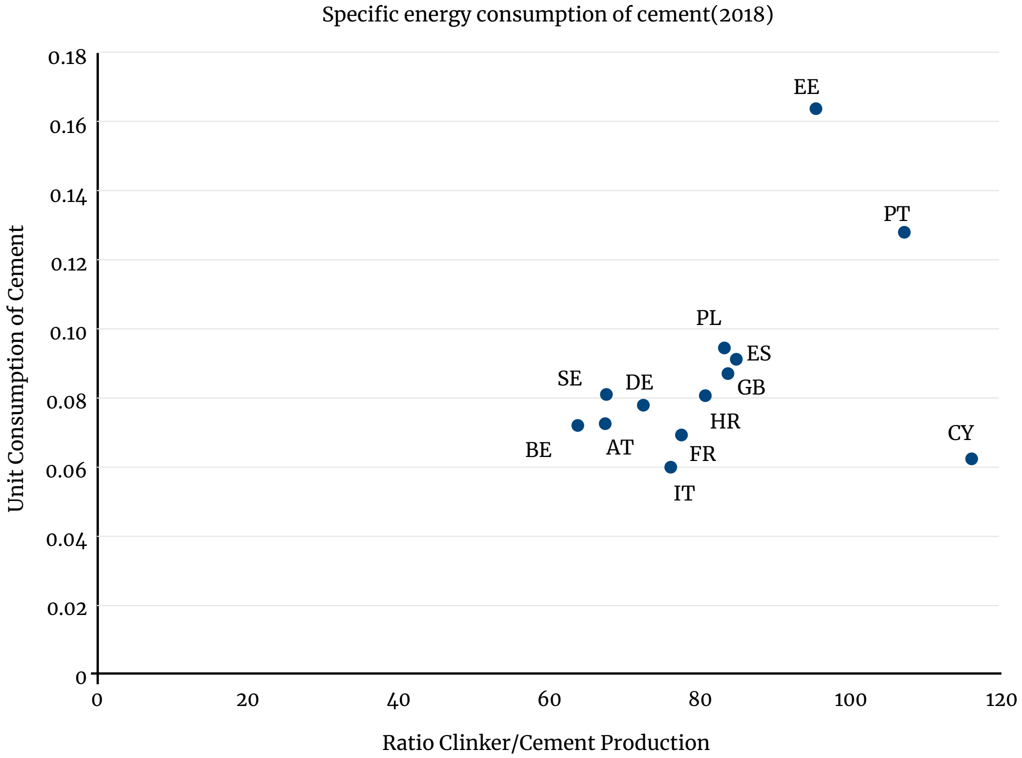
Source: (ADEME (Coordinator), 2021)

Since 2000, the following developments of unit consumption have been observed:

- There has been a slight decrease of the unit consumption of cement in Italy, Germany, Sweden, France, Croatia and Poland since 2000.
- Since 2007, countries strongly affected by the economic crisis (e. g. Portugal and Spain) show a sharp increase; the value remains stable at the EU level.
- There are considerable differences between the countries. These are partly due to **different efficiency levels in clinker** production, and partly due to different **clinker-cement ratio in cement production**: the higher this ratio, the higher the specific energy consumption.

The clinker-cement ratio and unit consumption (2018) for European countries are depicted in the following chart, which shows considerable differences in both figures – and thus different potentials for improvement - in different countries.

Figure 12: Correlation of Unit Consumption and Ratio Clinker/Cement Production in Europe 2018



Source: (ADEME (Coordinator), 2021)

Besides the clinker-to-cement ratio the types of fuels used are one important aspect when analyzing energy efficiency/CO2 reduction potentials. The following chart shows the development of fuel shares in Germany in the last decades. It can be seen that the share of fossil fuels has declined considerably, currently covering around one quarter of thermal energy input. At the same time, the use of alternative fuels[7] – as one major measure to reduce CO2 emissions - has increased considerably. **Specific electricity consumption** per tonne of cement remained more or less stable (around 100 kWh per tonne of cement) in the last decades, with an upward trend in the last years. The major reason for the increase to about **110 kWh** is the growing demand for finely-ground, high performance cements. Another aspect is the obligation to use additional filter technology which slows down the exhaust gas flow. Thus, more power is required to maintain the flow velocities. (Verein Deutscher Zementwerke, Hrsg., 2020)

On average, the s**hare of thermal energy**, compared to overall energy consumption (about 3200 KJ/kg cement, which is equivalent 0,88 MWh/t cement) is about **88%**. The remaining 12% can be attributed to electricity consumption.

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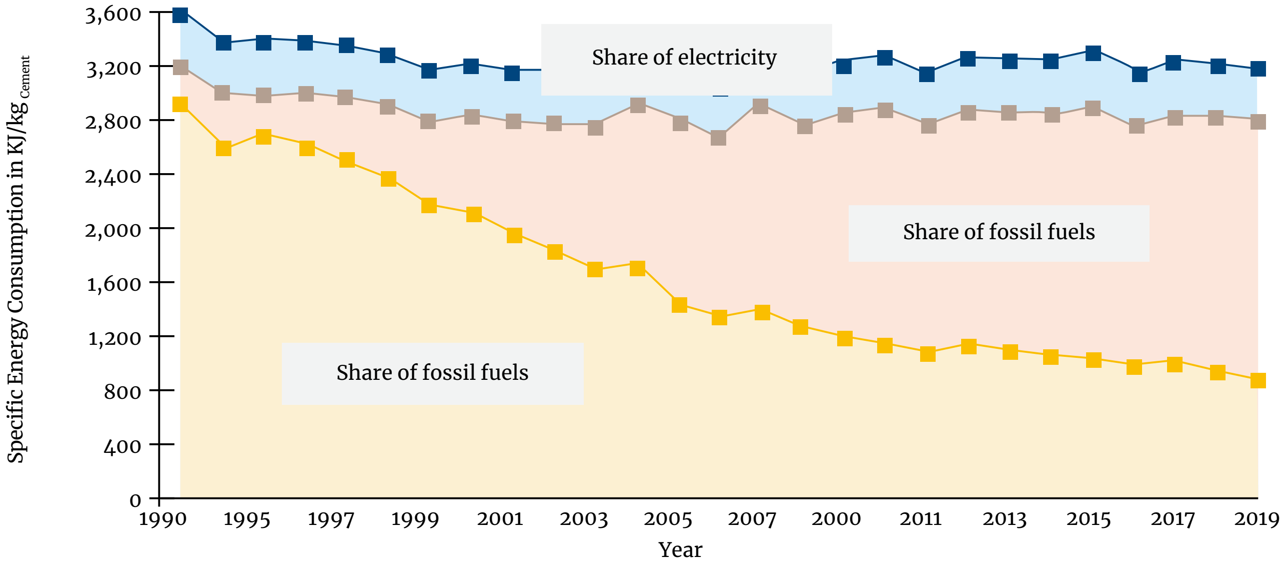
[7] Which have considerably lower specific emission factors than traditional fossil fuels and are thus attractive for companies covered by the EU-ETS.

Figure 13: Energy Consumption Shares in Germany



Source: (Verein Deutscher Zementwerke, Hrsg., 2020)

The EU-ETS system and its purpose to reduce CO2 emissions also plays an important driver to increase energy efficiency of cement production.

Table 6 shows current levels of some product benchmarks in the EU ETS (European Commission, 2021), which are defined in tonnes CO2 per tonne of product.

Additionally, the table indicates the average value of the 10 % most efficient installations. Comparing most efficient installations and benchmark values we can note some - limited - further room for reducing CO2 emissions related to cement production, especially for grey cement[8].

Table 6: Product Benchmarks

Product Benchmark	Average Value of the 10% Most Efficient Installations in 2016 and 2017 (t CO_2 equivalents/t)	Benchmark Value (Allowances/t) for 2021-2025
Grey Cement Clinker	0.722	0.693
White Cement Clinker	0.973	0.957

Source: (European Commission, 2021)

To summarize, there is still room for improvement at single mills' level, in terms of not only **(final) energy savings**, but also reduction of **greenhouse gas emissions**. This can be achieved through various ways: efficiency measures reducing final energy consumption, fuel switch (see chapter 4.3 on alternative fuels), production changes (refer to chapter 4.2 on use of alternative raw materials) and further initiatives such as Carbon Capture and Storage (see section 4.10).

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[8] White cements are made from raw materials that are very low in iron (Fe_2O_3 content <0.1%) and are mainly used for terrazzo, exposed concrete and plaster. White cement is not only suitable for light-coloured preparations, it is also much easier to colour with coloured pigments than ordinary grey Portland cement. The production of white cement is much more complex than grey cement and delivers much lower outputs with the same plant size (factor 3 to 4 compared to grey cement). Source: Wikipedia

In an effort to achieve an overall carbon reduction as depicted in the "2 DS Scenario"[9] in the Technology Roadmap for a low-carbon Transition in the Cement Industry (IEA, 2018) it is assumed that the major game changer will be innovative technologies (such as carbon capture and storage, reduction of 48% of CO_2), followed by the reduction of the clinker to cement ratio (minus 37%) and fuel switching. Improving energy efficiency to best available technology shall also contribute to the overall reduction target. Its contribution is equivalent to 12% of current direct CO_2 emissions of global cement production.

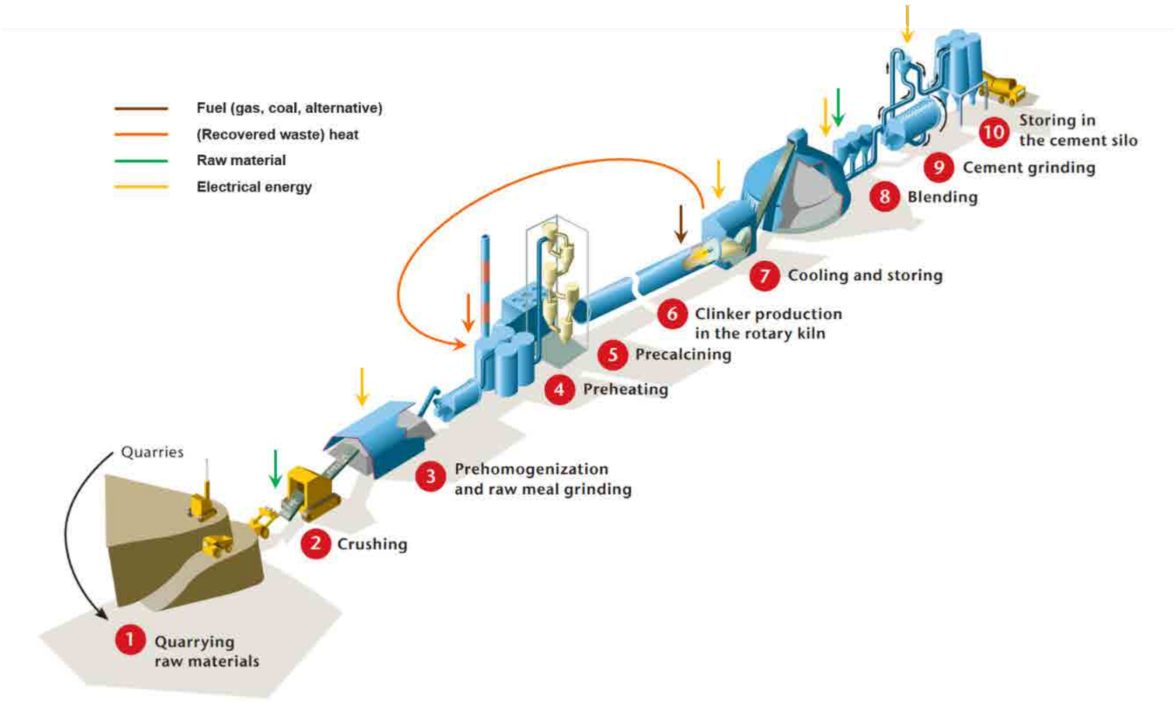
3.2.2 Energy Flows

The cement industry is highly energy-intensive, consuming energy in the form of power as well as fuels. Sector-specific energy saving measures presented in the following chapters focus on the cement production process (while not considering cross-cutting technologies such as efficient motors), along with the energy supply relevant for this sector.

The cement industry uses fuel, (waste) heat and electricity. Electrical energy is primarily used for grinding processes (raw material and finish grinding). Fuel input (either fossil fuels or alternative fuel) is required in the clinker production process.

The following chart gives an overview of the major energy flows (simplified):

Figure 14: Overview Energy and Material Flows



Adapted from: (IEA, 2018)

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[9] Energy system pathway with at least 50% chance of limiting the average global temperature increase to 2°C compared to the baseline scenario

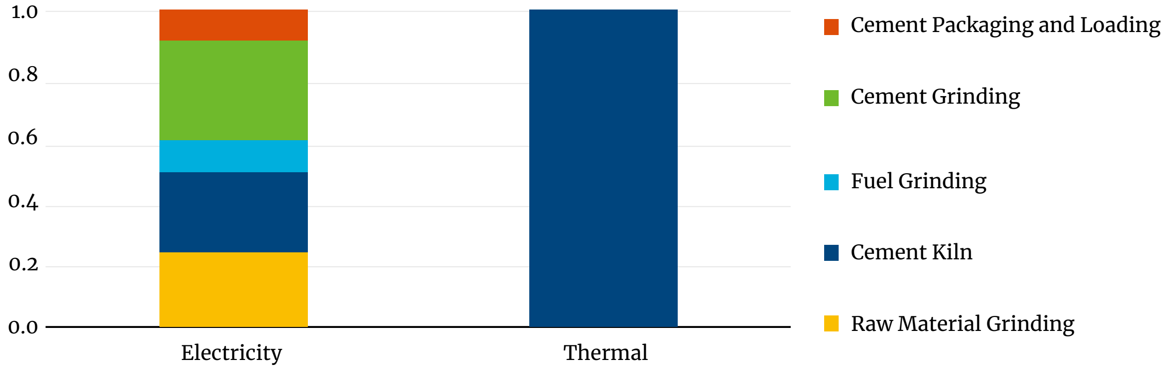
3.2.3 Energy Intensive Processes

When analyzing specific energy saving potentials and measures, one of the first steps is to identify major energy consuming processes in the respective sector.

As shown in Figure 15, it is obvious that the overall thermal energy consumption is attributable to the cement kiln. Electricity consumption is split over all process steps, with focus on raw material and cement grinding.

Typical thermal energy consumption in Europe amounts to 3500 GJ/tclinker (972 kWh), achievable best practice to 2900-3300 GJ/$t_{clinker}$ (805-916 kWh); thermodynamic minimum is set at 1700-1800 GJ/tclinker (472-500 kWh). Electricity consumption amounts to 100 kWh/t_{cement} (Tobias Fleiter, 2013).

Figure 15: Relevance of Process Steps for Energy Consumption



Source cited in: (IEA, 2018)[10]

Major points influencing specific energy consumption according to the BAT document (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013) comprise:

- size and plant design (cyclone stages, calciner, tertiary air, compound operation of the mill, length to diameter ratio of the kiln, type of clinker cooler, throughput of the kiln)
- moisture content of raw materials and fuels
- raw material properties, such as burnability
- type of clinker
- homogenizing and precise metering of kiln feed material and fuels
- optimization of process control including flame cooling
- bypass rate
- Fuel mix composition and parameters (moisture content especially when comparing fossil fuels and alternative (waste derived) fuels, reactivity or coarseness, calorific value of the fuels)

The main users of electricity are the mills (finish grinding and raw grinding) and the exhaust fans (kiln/raw mill and cement mill, which altogether constitute more than 80 % of the electrical energy usage.

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[10] Diagram refers to different values for 100% (thermal energy consumption and electricity consumption)

4

Sector Specific Energy Efficiency Measures

Table 7 presents the energy efficiency measures analysed in this chapter. Each chapter explains the baseline situation, the measure and its potential in terms of energy saving and greenhouse gas emission.

Table 7: Cement Sector Energy Efficiency Measures

Chapter	Measure	Process
4.1	High Efficiency Separators and Classifiers	Raw Material Preparation / Finish Grinding
4.2	Blended Cement Alternatives	Raw Material Preparation
4.3	Alternative Fuels Co-Processing	Fuel Preparation
4.4	Process Control Optimization in Clinker Making	Clinker Making
4.5	Kiln Shell Heat Loss Reduction (Improved Refractories)	Clinker Making
4.6	Low-Pressure Drop Cyclones for Suspension Preheaters	Clinker Making
4.7	Oxygen Enrichment Technology	Clinker Making
4.8	Optimized Waste Heat Recovery (WHR) in Clinker Cooler	Clinker Cooling
4.9	Vertical Roller Mills for Finish Grinding	Finish Grinding

4.1 High Efficiency Separators and Classifiers

4.1.1 Description of Baseline Situation and Energy Consumption

Separators and Classifiers are relevant both for raw material preparation and finishing grinding applications. Their functionality has to be examined in close relationship with the applied grinding technology. Some grinding applications (vertical roller mills, also refer to section 4.9) integrate both classifying and grinding.

In general, the purpose of separation is to separate particles by their size. It is defined as follows: “to differentiate particles according to their size exploiting the fact that different particles can obtain different velocities when moving in a fluid under a certain force. Air separation is the method of separating dry particulate materials into two distinct size fractions, one above and the other below a defined cut-point, which normally range from 1 micron to 300 microns.” (Hardy, 2021) Several industries such as cement, coal, ceramic, pulp and paper, fertilizer and pharmaceutics use this technology.

These devices separate the mill output into coarse and fine fractions. Fines can be removed as soon as they are produced and the coarse returns for further grinding. Moreover, separators can be used to also achieve specific product characteristics, e.g. a more suitable particle size distribution. In many applications, separation is used for enhancing the operation of some other process. (Hardy, 2021)

In principle, there are static separators and dynamic separators. Static separators do not have any moving parts and can be adapted only via mechanical modifications. Dynamic separators are available as first generation (turbo) separators, second generation (cyclone) separators and third generation (cage type or **high efficiency) separators**.

First generation classifiers were equipped with an internal fan and had low separation efficiencies of 50-60%. Second generation classifiers (60-75% separation efficiency) have improved air re-circulation and separate centrifugal movement (Worrell, Kermeli, & Galitsky, 2013).

4.1.2 Suggested Measures of Improvement

The suggested measure of improvement is the use of high efficiency separators for new mills or the replacement of less efficient separators by third generation high-efficiency separators. These classifiers can reach up to **80-90% separation efficiency** and have an improved air distribution system as well as advanced control of the air flow. The material stays longer in the separator, which leads to sharper separation and reduced overgrinding. (Worrell, Kermeli, & Galitsky, 2013)

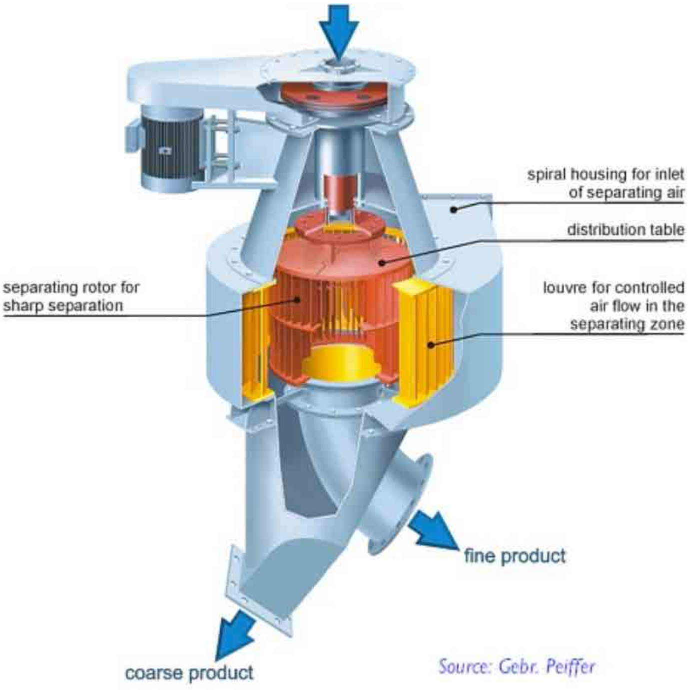
These separators were developed in the beginning of the 1980s. Similar to the second generation, an external fan produces the air flow required for the separation. Suitable continuous conveyors feed the material in the separator. Fine particles are conveyed by air in external cyclones or directly to a bag filter. The main separating device is a **cylindrical rotor**. The rotor, which is operated by a variable speed drive, is like a cage composed of blades closely spaced. The rotor speed determines swirl in the classifying zone and therefore the cut of the separator.

The material is normally fed at the top of the separators. Material enters the separator and is dispersed in the circulating air by the distribution plate. The particles are driven by three forces:

- the centrifugal force from the dispersing plate (which tries to push the material towards the guide vanes)
- the drag force from the air flow (which tries to pull the material into the rotating cage) and
- the gravity due to the mass of the particle.

The coarse material does not enter the rotating cage but instead leaves the classifier by gravity up to the bottom device (cone or other). The fine material enters in the cage and exits with the air flow by the upper or lower part of the separator. The below picture shows an example of a high efficiency classifier. (The Cement Grinding Office, 2021)

Figure 16: High Efficiency Classifier



Source: Gebr. Pfeiffer, cited in: (Institute for Industrial Productivity, 2021)

4.1.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Replacing a conventional classifier with a high-efficiency classifier can lead to 15% increase in the grinding mill capacity and improved product quality owing to a more uniform particle size both in raw meal and cement. A better size distribution in the raw meal may also lead to fuel savings in the kiln and improved clinker quality. (Worrell, Kermeli, & Galitsky, 2013)

Net energy savings are expected to lie in the range of 10-15% or a decrease of 2.3-4.5 kWh per tonne product[11].

Investment costs estimations vary between 2-3 USD/annual tonne raw material production (Worrell Ernst, 2013) to 2 million EURO for the retrofit of a plant with a capacity of 2 Mio t/a, which would mean approximately 1 EURO/annual tonne (European Cement Research Academy, Cement Sustainability Initiative Ed., 2017).

Table 8: Key Facts of Measure – High-Efficiency Separators and Classifiers

Key Facts of Measure – High Efficiency Separators and Classifiers	
Investment Cost:	1-2.5 EURO/$t_{product}$
Energy Savings: (Electricity)	2.3-4.5 kWh/$t_{product}$
CO_2 Mitigation:	1.1-2.3 kg CO_2/$t_{product}$
Advantage:	• Reduction of electricity consumption • Increase of throughput • Improved product quality
Disadvantage:	• Difficulty to reach optimum seal system • Physical layout of the grinding system must allow retrofitting

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[11] overall electricity savings minus additional electricity consumption in the classifier of about 5-8% of grinding energy

4.2 Blended Cement Alternatives

4.2.1 Description of Baseline Situation and Energy Consumption

The **clinker to cement ratio** describes the share of clinker in cement on a mass basis. Clinker hardens the cement when it is mixed with water and is the main constituent of most cement types. Due to process emissions from the clinker production process and (thermal) energy related emissions from its production, switching (partially) from clinker to other – less CO2 intensive – components are one of the major levers to reduce CO2 emissions arising from cement production. (IEA, 2018)

Specific clinker to cement ratios are defined for specific types of cement, depending on the mechanical and durability requirements of the respective final products or applications. Portland Cement typically contains 90% clinker, together with gypsum and fine limestone. Blended cement alternatives have a lower clinker share and thus a lower CO2 footprint. Potential alternative sources are:

- Granulated Blast Furnace Slag (GBFS, generated in the production of pig iron)
- Fly ash (from coal fired power plants)
- Natural pozzolanic materials
- Limestone
- Calcinated clay.

Following the European Norm DIN EN 197-1 five main types of cement are defined (Diethelm Bosold, 2017):

- Portland cement CEM I
- Portland composite cement CEM II
- Blast furnace cement CEM III
- Pozzolan cement CEM IV
- Composite cement CEM V.

The respective components and shares are given in the below table.

Table 9: Cement Types according to DIN EN 197-1 (translated) (Diethelm Bosold, 2017)

Cement Type			Main Ingredient Besides Portland Cement Clinker	
Main Type	**Name**	**Abbreviation**	**Type**	**Portion [M.-%]**
CEM I	Portland cement	CEM I	-	0
CEM II	Portland slag cement	CEM II/A-S	Slag sand (S)	6 … 20
		CEM II/B-S		21 … 35
	Portland silica cement	CEM II/A-D	Silica dust (D)	6 … 10
	Portland pozzolana cement	CEM II/A-P	Natural pozzolana (P)	6 … 20
		CEM II/B-P		21 … 35
		CEM II/A-Q	Natural tempered pozzolan (Q)	6 … 20
		CEM II/B-Q		21 … 35
	Portland fly ash cement	CEM II/A-V	Fly ash rich in silicic acid (V)	6 … 20
		CEM II/B-V		21 … 35
		CEM II/A-W	Lime-rich fly ash (W)	6 … 20
		CEM II/B-W		21 … 35
	Portland black slate	CEM II/A-T	Black slate (T)	6 … 20
		CEM II/B-T		21 … 35
	Portland limestone cement	CEM II/A-L	Limestone (L)	6 … 20
		CEM II/B-L		21 … 35
		CEM II/A-LL	Limestone (LL)	6 … 20
		CEM II/B-LL		21 … 35
	Portland composite cement	CEM II/A-M	All main components are possible (S, D, P, Q, V, W, T, L, and LL)	12 … 20
		CEM II/B-M		21 … 35
CEM III	Blast furnace cement	CEM III/A	Slag sand (S)	36 … 65
		CEM III/B		66 … 80
		CEM III/C		81 … 95
CEM IV	Pozzolana cement [1]	CEM IV/A	Silica dust, pozzolana and fly ash (D, P, Q, V, and W	11 … 35
		CEM IV/B		36 … 55
CEM V	Composite cement	CEM V/A	Slag sand (S)	18 … 30
			Pozzolana, fly ash (P, Q, V)	18 … 30
		CEM V/B [2]	Slag sand (S)	31 … 49
			Pozzolana, fly ash (P, Q, V)	31 … 49

1: The proportion of silica dust is limited to 10 M-.%

2: The proportion of clinker must be between 20 and 38 M-.%

4.2.2 Suggested Measures of Improvement

The suggested measure of improvement relates to the substitution of clinker by other input materials. Resulting cement properties (especially the calcium content and content of other main elements) need to be **suitable for the specific application** in terms of durability and strength. Further factors to be considered are the possibilities and cost of further treatment of the alternative raw materials and their local or regional availability.

Given the overall aim of decarbonizing industrial and energy processes, we can expect that the **availability** of blast furnace slag or fly ash from coal power plants will reduce within the next decades. It is assumed that the iron and steel sector will move from blast furnace processes to more efficient electric arc furnaces and that coal power plants will be substituted by other ways of power production.

The availability of natural pozzolanic materials (from volcanic compounds or sedimentary rocks; ash from agricultural residues and silica fumes) depends on local conditions as well as competition with other industrial applications.

Moreover, the following restrictions should be considered (IEA, 2018):

- **Granulated Blast Furnace Slag** can be integrated at high portions (95% on a mass basis). Flight ash can be used up to 25-30%, while considering rather varying quality worldwide; both types require higher electricity consumption compared to Portland cement due to additional process steps. However, these efforts are by far offset by thermal energy savings.
- The extent of using **limestone** instead of clinker typically reaches 25-35% of mass content, but could be extended to up to 50%.
- Using **calcined clay** has a long history dating back to bridge constructions in the 1930s in San Francisco. Current applications point at optimised combinations of calcined clay and limestone which can displace clinker by up to 50% without changing cement properties.

The IEA status report[12], which also indicates a worldwide average clinker to cement ratio of about 0.7, states the following starting point for China:

“Although China has one of the lowest clinker-to-cement ratios globally, its ratio rose from 0.57 to 0.60 during 2014-2017, then to 0.64 in 2018. The main causes are overcapacity, which reduces momentum for more blending to replace clinker, and changes to cement standards, which have eliminated a grade of composite cement.”

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[12] https://www.iea.org/reports/cement

4.2.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Substituting clinker by other, less CO2 intensive raw materials reduces overall energy consumption and CO2 emissions (both in terms of process emissions and thermal energy for the calcination process). However, it requires additional process steps (grinding, mixing) which leads to an (slight) increase in electricity consumption.

Relevant investment costs comprise costs for storage and handling of the alternative raw materials. Operational costs include the costs for the alternative material and above-mentioned electricity costs, but also savings in terms of the replaced material. Additional costs such as wear and tear are not considered in the below estimation. (European Cement Research Academy, Cement Sustainability Initiative Ed., 2017).

We further expect that carbon pricing will play a major role in subsequent cost-benefit analyses. Actual results will heavily depend on the specific input material and competing applications.

Table 10: Key Facts of Measure – Blended Cement Alternatives

Key Facts of Measure – Blended Cement Alternatives	
Investment Cost:	0-6 million EURO/$t_{clinker}$; Operational costs increase by 0-4.2 EURO/$t_{clinker}$
Energy Savings: (Thermal and Electricity)	100-400 MJ/$t_{clinker}$ (30-110 kWh/$t_{clinker}$) decrease of thermal energy demand 0-3 kWh/$t_{clinker}$ increase of electrical energy demand
CO_2 Mitigation:	100 kg CO_2/$t_{clinker}$ (10-15% replacement of raw material by GBPS)
Advantage:	• Considerable reduction of thermal energy demand and process emissions • Partly use of waste materials
Disadvantage:	• Not all types of cement are suitable for all types of applications • Additional process steps required (grinding, blending), additional quality assurance • Difference in local availability of alternative raw materials (quality/quantity) • Reduced availability of GBFS and fly ash in the future due to expected production changes

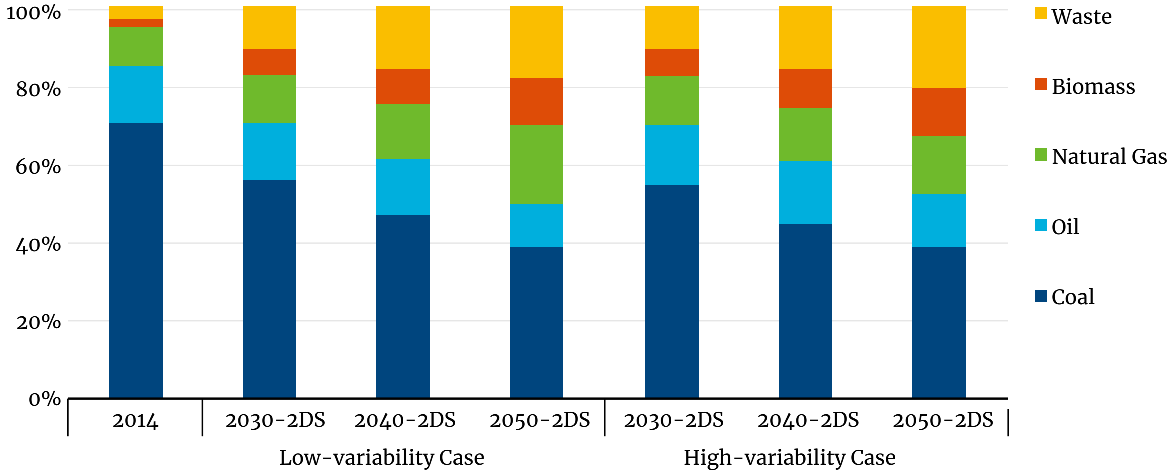
4.3 Alternative Fuels Co-Processing

4.3.1 Description of Baseline Situation and Energy Consumption

On a global level, coal is the most widely used fuel in cement production, corresponding to 70% of global thermal energy consumption. Oil and gas together add up to 25%. Biomass and waste (in the following also called alternative fuels) can, in principle, substitute fossil fuels which are currently used for cement production.

Following IEA Roadmap analysis (IEA, 2018) there is the potential to reduce the share of fossil fuels by 24% by 2050 and to reduce the CO2 emission due to thermal energy demand for cement production from 0.088 to 0.058 tCO2/GJ. The global thermal energy mix in cement and its anticipated development in the 2DS scenario[13] is shown in the following chart.

Figure 17: Global Thermal Energy Mix for Cement Production in 2DS Scenario



Note: Waste includes biogenic and non-biogenic waste soures.

Source: Base year data from CLL, WBCSD and IEA (fprthcoming), Status Update Project from 2013 Low-Carbon Technology for the India-Cement Industy; CSI(2017), Global Cement Database on CO2 and Energy Information, www. wbcsdcement. org/GNR; SNIC (forthcoming), Low-Carbon Technology for the Brazilian Cement Industry; data submitted via personal communiction by Sinoma Research Institute and China Cement Association (2016-2017).

Source cited in: (IEA, 2018)

Currently, about one third of fuel input in the EU cement industry are alternative fuels. This share has seen a constant increasing trend since 1990. Some countries such as Germany or the Czech Republic already report shares of more than 60%. From a purely technical perspective, substitution rates of 80% (on an average annual basis) are reported to be feasible. (Cembureau, 2021)

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[13] Energy system pathway with at least 50% chance of limiting the average global temperature increase to 2°C

4.3.2 Suggested Measures of Improvement

Technical Issues

The suggested measure of improvement, which combines aspects of energy efficiency, resource efficiency and carbon emission reduction, relates to the (further) replacement of fossil fuels by biomass or waste. The following waste types can be used:

- Discarded or shredded tires
- Waste oils and solvents
- Industrial waste including lime sludge from paper industry
- Non-recyclable plastics, textiles and paper residues
- Fuels derived from municipal solid waste
- Effluent treatment sludge from water and wastewater treatment plants.

Some major aspects of importance when using these types of fuel are(Shahri, 2020):

- **MSW (municipal solid waste)** is not a homogenous source and contains shares of combustible fractions (e.g., wood residues, plastics, cardboard, rubber, and paper), inert materials (e.g., ceramics, sand, stone, ferrous/non-ferrous metals), wet organic materials and also hazardous fractions, such as tar, resins, impregnated sawdust, or non-hazardous materials. The quantity and quality of MSW are highly diverse across different countries and even cities and not all types of MSW are suitable for co-processing.

- **Plastic waste** is easier to handle than MSW and has higher heating values, ranging from 17 – 40 GJ/t depending on the exact composition and the moisture content. The main problem with plastic however, is the formation of substances like dioxins and furans that can present health hazards. The formation of these substances depends on the waste composition and the combustion temperatures.

- **Waste oil** has a high calorific value and is easy to store and handle, which makes it an attractive option. Potential sources cover waste resulting from exploration, quarrying, mining and physical and chemical treatment of minerals; from the fur, leather and textile industries, from natural gas purification, petroleum refining and pyrolytic treatment of coal.

Other biomass types such as fast-growing species (e. g. specific wood type) are possible in theory but currently not economically feasible. Also, co-processing of hazardous waste is, in principle, possible. However, the focus is then rather on the disposal than on the thermal use.

From a technical perspective, two aspects are important when selecting alternative fuels: the **calorific value** and the **moisture content**. Substitution of fossil fuels by alternative fuels might lead to an increase in the thermal energy demand due to lower calorific values and higher moisture contents. A minimum average calorific value of 20-22 GJ/t fuel is required for firing in the kiln; pre calciner kilns operate at lower process temperatures and thus can also integrate 60% of fuels at lower calorific values. In the pre-calciner, minimum calorific values should exceed approximately 13 GJ/t.

Additionally, **pre-treatment of alternative fuels** is often required to secure combustion efficiency and to minimise problematic substances (e. g. high concentration of chlorine or other trace substances or management of metals). This pre-treatment means additional process steps (grinding, drying) which also leads to additional energy consumption and costs. These factors have to be weighed against the savings resulting from the use of alternative fuels.

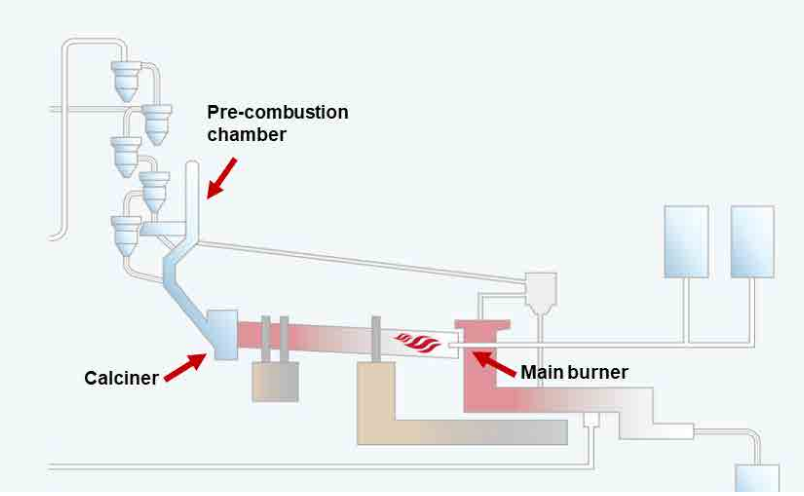
High substitution rates of alternative fuels (65% and more) might lead to **operational problems** in the kiln system. Fuels with high concentrations of chlorine and sulphur might lead to increased coating formation in the kiln inlet, gas riser duct and the lower cyclone stages. This fact requires additional cleaning efforts or the installation of a bypass in the kiln inlet. (European Cement Research Academy, Cement Sustainability Initiative Ed., 2017)

Feed in Points

Waste fuels and raw materials must be introduced at the most suitable points in the process, depending on the temperature requirements. The most common ones are:

- through the main burner at the rotary kiln outlet end
- through a feed chute at the transition chamber at the rotary kiln inlet end (for lump fuel)
- through secondary burners to the riser duct
- through pre calciner burners to the pre calciner
- through a feed chute to the pre calciner (for lump fuel)
- through a mid-kiln valve in the case of long wet and dry kilns (for lump fuel) (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2017) (Shahri, 2020)

Figure 18: Kiln and Cyclones Structure



Source: adopted by (Shahri, 2020) (Durag Group, 2019))

Framework Conditions

Apart from mere technical questions, the use of alternative fuels also requires adequate framework conditions, such as:

- Waste management legislation that promotes waste recovery instead of disposal
- Availability of controlled waste collection, treatment and processing including local waste collection (including monitoring)
- Reduced bureaucracy when obtaining a permit for the use of alternative fuels[14]
- Social acceptance of co-processing waste fuels in cement plants (requires clear information and emission monitoring) (IEA, 2018), but also
- CO2 legislation and CO2 pricing.

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[14] Current requirements are analysed in depth in the study from Umweltbundesamt Germany (https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2020_11_05_texte_202_2020_abfallverbrennung_zementwerke_1.pdf)

4.3.3 Potential Energy Savings and Greenhouse Gas Emission

Substitution of fossil fuels by alternative fuels (assumption: 65% substitution rate) can lead to overall increase of (final) energy demand, but reduction in fossil fuel demand and thus GHG savings. Investment cost (retrofit) is based on a clinker capacity of 2 million t/a. Operational costs (fuel costs only) are expected to be reduced based on the assumption that the cost of alternative fuel is less than the coal price. (European Cement Research Academy, Cement Sustainability Initiative Ed., 2017)

Table 11: Key Facts of Measure – Alternative Fuels Co-Processing

Key Facts of Measure – Alternative Fuels Co-Processing	
Investment Cost:	• 5-15 million EURO (retrofit; clinker capacity 2 mt/a) • reduction of operational cost by 2-2.5 EURO/$t_{clinker}$
Energy Savings: (Thermal and Electricity)	• Reduction of fossil fuel consumption[15] • Increase of overall thermal energy demand: by 200-300 MJ/$t_{clinker}$ • Increase of overall electric energy demand: by 2-4 kWh/$t_{clinker}$
CO_2 Mitigation:	• 1.42-1.8 t CO_2/t RDF (substitution of coal) • 30-50 kg CO_2/$t_{clinker}$
Advantage:	• Reduction of fossil fuel consumption • Higher material efficiency, less waste disposal
Disadvantage:	• Partly higher thermal energy demand compared to fossil fuels • Additional process steps for fuel preparation (drying, grinding) • Potential operational problems at high substitution rates • Hard to implement when framework conditions are not yet in place (legislation, waste collection/availability and monitoring, social acceptance)

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[15] 15-19 GJ/t RDF substituting coal (Institute for Industrial Productivity, 2021)

4.4 Process Control Optimization in Clinker Making

4.4.1 Description of Baseline Situation and Energy Consumption

Clinker production is extremely energy intensive. Non-automated or non-optimum process control systems lead to heat losses, unstable process conditions, and more operational stops. The final effects lead to increased fuel demand of the system. Also, the lifetime of the equipment (the refractory lining, for example) depends on the process condition. Without an optimal process, emissions like NOx and SO2, as well as dust will increase.

4.4.2 Suggested Measures of Improvement

Process Control Systems are effective measures to optimize combustion processes and conditions and to maintain operating conditions in the kiln at optimum levels. Improved process control will also help to improve the product quality and grindability, e. g. reactivity and hardness of the produced clinker, which leads to more efficient clinker grinding. Reduction of emissions, such as NOx, SO2, and dust, are secondary effects of this optimization (International Finance Corporation (IFC), 2017) (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013).

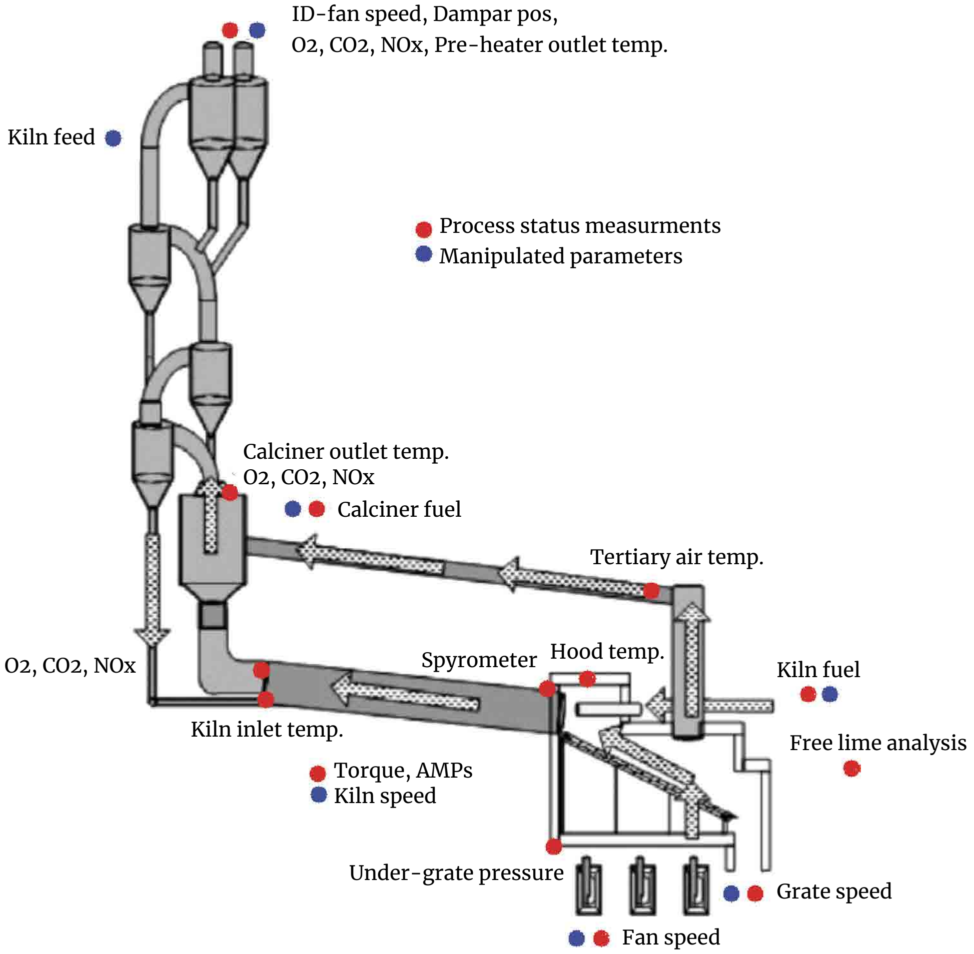
Reduced flame and burning temperatures cause fuel consumption reductions. Furthermore, NOx emissions can be reduced. Modern process control systems with faster measuring and control equipment can allow higher switch-off criteria and thereby reduce the number of CO trips. Avoidance of kiln upsets and CO trips when electrostatic precipitators are applied reduces dust emissions. In doing so, it also reduces the emissions of any substances adsorbed to the dust, for example, metals.

Process control optimization applies to all kilns and includes instruction/training of the kiln operators and techniques such as homogenizing the raw material, ensuring uniform coal dosing, and improving the cooler's operation. To ensure that the feed rate of solid fuel is steady with minimal peaks, it is essential to have good designs of hoppers, transport conveyors, and feeders, such as a modern, gravimetric solid fuel feed system (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013).

Additional process control systems include the use of online analysers that permit operators to determine the chemical composition of raw materials and the product, thereby allowing for immediate changes in the blend of these materials.

Besides automating the weighing and blending processes of raw materials, other parameters such as air and mass flow and temperature distribution can be controlled to optimize kiln operation. Control points and parameters in a kiln system control and management system can be seen in the scheme below.

Figure 19: Control Points and Parameters in a Kiln System Control



Source: Adapted from (International Finance Corporation (IFC), 2017)

Several management systems are marketed through the cement industry manufacturers and are available and in use across the globe. Modern systems use so-called "fuzzy logic" or expert control, or rule-based control strategies. Expert control systems do not use a modelled process to control process conditions, but try to simulate the best human operator, using information from various stages in the process.

Modern versions of process control and optimization systems make use of advancements in information and communication technologies and enable real-time monitoring and adjustment of process parameters by multiple users (National Development and Reform Commission of China, 2012).

4.4.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

There are no barriers to installing advanced process controls on new construction. Most of the existing facilities should be able to retrofit the operations to accommodate control systems.

Thermal energy savings from process control systems may vary between 2.5 % and 10 %, and the typical savings are estimated at between 2.5 % and 5 % (International Finance Corporation (IFC), 2017). In addition, electricity consumption can be reduced by up to 2 kWh per tonne of clinker (Forschungsgesellschaft für Energiewirtschaft mbH (FfE), 2019).

In a 4,500 tonne per day Chinese plant, with the installation of a process control and optimization system, annual energy consumption was reduced by 395.6 terajoules (109 GWh). The installation required an investment of 125.000 EURO and took one month to complete. The system provided annual savings of 1 million EURO, resulting in a payback time of two months (International Finance Corporation (IFC), 2017).

Table 12: Key Facts of Measure – Process Control Optimization in Clinker Making

Key Facts of Measure – Process Control Optimization in Clinker Making	
Investment Cost:	125.000 EURO (plant with capacity of 4,500 tonne per day)
Energy Savings: (Thermal and Electricity)	• Thermal: 2.5-10 %, 32 kWh/$t_{clinker}$ (Spec. potential savings) • Electrical: 2 kWh/$t_{clinker}$
CO_2 Mitigation:	2.9-5.9 kgCO_2/$t_{clinker}$
Advantage:	• Improve heat recovery • Improve material throughput • Reliable control of free lime content in the clinker • Decrease fuel consumption • Decrease refractory consumption • Lower maintenance costs
Disadvantage:	• A high educational level of operators and staff is critical for process control and optimization.

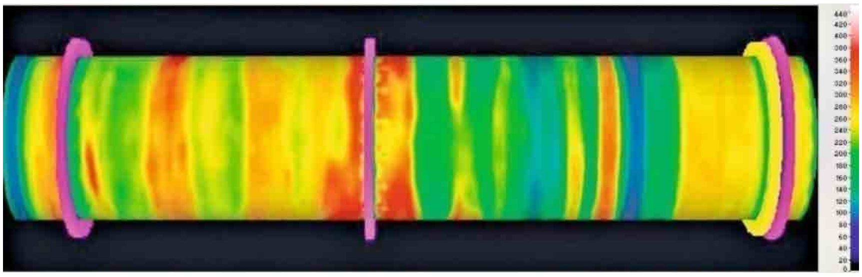
4.5 Kiln Shell Heat Loss Reduction (Improved Refractories)

4.5.1 Description of Baseline Situation and Energy Consumption

In any cement plant, the rotary kiln is the main section where all the thermal energy is used and various chemical reactions are involved in the process of clinker manufacturing. When the kiln is operating, there is a significant difference between kiln shell temperature and ambient temperature. The temperature required inside the kiln for necessary chemical reactions is about 1450 °C.

In the burning zone, there are considerable heat losses. The major heat losses comprise heat losses by the kiln exhaust gas (10-20%), hot air from the cooler stack (5-10%), combined radiative and convective heat from kiln surfaces (more than 40%). When all the heat losses are considered, the kiln operates at a low efficiency of around 30-50% (Oorja energy engineering service, 2021) (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013).

Figure 20: Rotary Kiln Shell Surface Temperature Monitoring



(Source: (ZKG-Bauverlag, 2021))

The figure below shows the heat loss of an investigated cement kiln[16] in the calcination zone for 19 days. The kiln has a dimension of 4 m × 60 m with an inclination angle of 2.29°. It is fired by pulverized coal and operated mostly with a slow rotational speed (n = 3–3.8 rpm) and has a production capacity of 2500 tonne s/day.

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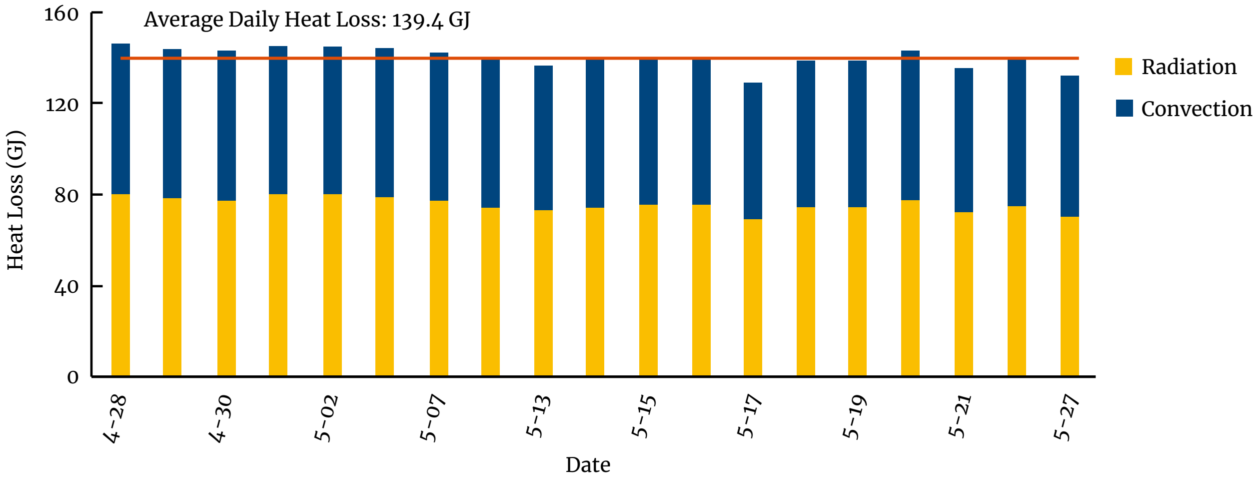
[16] A typical dry kiln with five stage cyclone preheater and pre-calciner in a local cement company (Jiangxi province, China) is considered as a case study.

Figure 21: Daily Heat Loss through a Kiln Shell (2500 tonne Clinker/day)



Source: (Wua, Xiao-YanLiu, Hu, Zhang, & Lua, 2019)

The average daily heat loss of the investigated cement kiln is 140 GJ (38 MWh), which means that 0.05 GJ (14 kWh) thermal energy is lost through the kiln when producing one tonne of clinker (Wua, Xiao-YanLiu, Hu, Zhang, & Lua, 2019).

4.5.2 Suggested Measures of Improvement

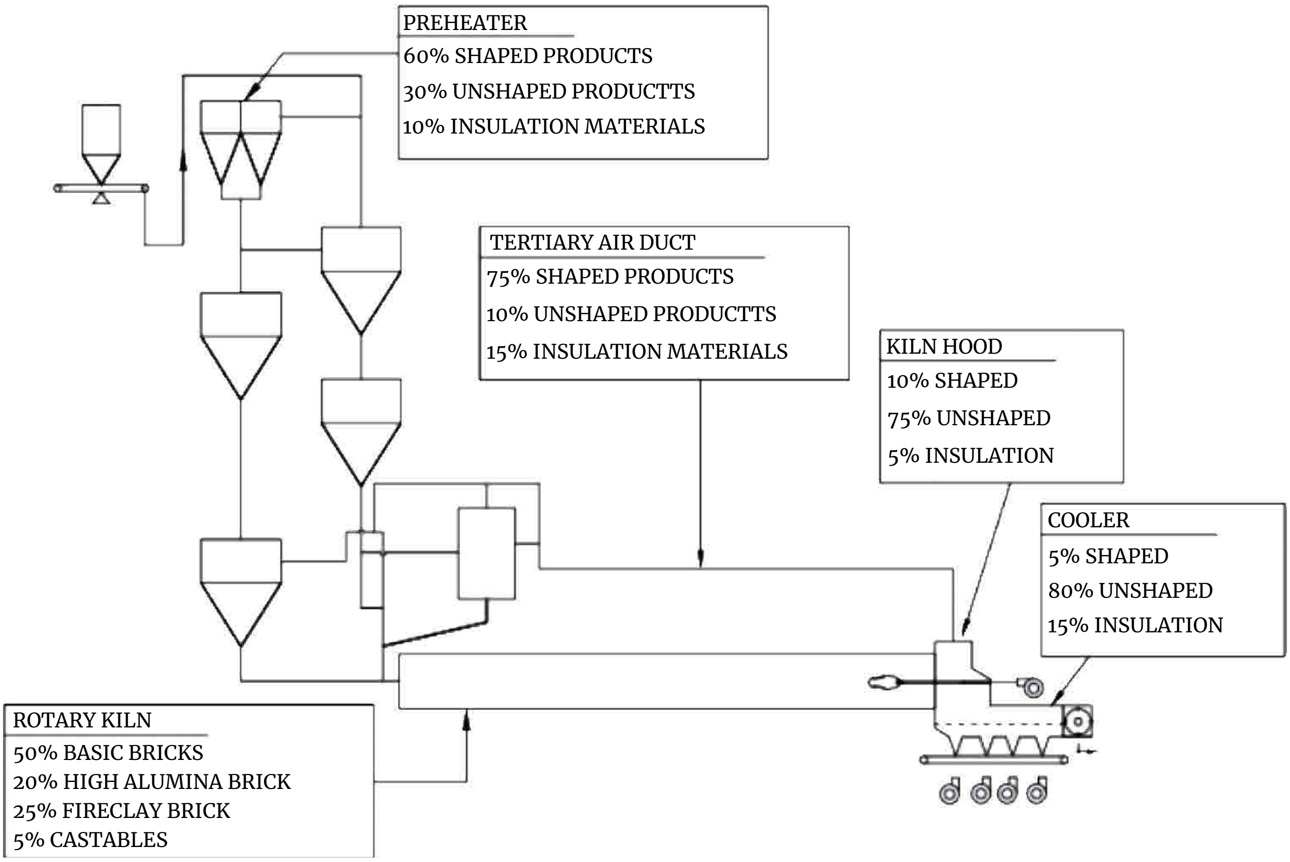
In order to protect kiln's steel shell from high temperatures inside a kiln (occurring during the clinker manufacturing process), refractory lining is necessary. Refractory is a material, usually non-metallic, that is suitable to withstand high temperatures. In a kiln, the refractory usually consists of brick of special composition and sizes.

The use of better insulating refractory materials (e. g. Lytherm) can reduce heat losses. The choice of refractory material is a matter of the insulating properties of the brick and the ability to develop and maintain a coating. The coating helps to reduce heat losses and protects the burning zone refractory bricks.

The choice of refractory material depends on the combination of raw materials, fuels, and operating conditions. Refractories should always be designed and installed to provide a balanced and predictable economic life. The shutdown of the kiln due to the refractory problem requires the total cool down of the kiln, which is very problematic and expensive.

Because of wide spectrum of characteristics such as size, capacity, raw materials, fuels used, and operational practices, it is not possible to provide a standard recommendation for refractory use to which any plant can adhere. Nonetheless, it is good to follow a general guideline that improves the refractory performance in each zone of the kiln and all other ancillary equipment with minimum cost and minimum failure of refractory lining.

Figure 22: Refractories Used in Different Application Areas in a Cement Plant



Source: (Routschka & Wuthnow, 2012)

4.5.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Estimates suggest that the development of high-temperature linings for the kiln refractories can reduce the fuel use by 0.12 to 0.4 GJ/tclinker (33 to 111 kWh/tclinker). Changjiang Cement Factory in Zhejiang City, Jiangsu Province applied energy-saving kiln lining to its shaft kiln and found energy savings of 0.46 to 0.63 GJ/tclinker (127 to 175 kWh/tclinker). In addition to these energy savings, they were able to increase the production (Worrell, Galitsky, & Price, Energy Efficiency Improvement Opportunities for the Cement Industry, 2008) (Worrell, Kermeli, & Galitsky, 2013). Refractories are made by foreign companies operating in China, particularly in Liaoning Province, such as Refratechnik (German) and RHI (Austrian).

Costs for improved refractories systems are estimated to be 0.20 EURO/annual tonne clinker capacity. Structural considerations may limit the use of new refractory materials. Extended lifetime of the higher quality refractories will lead to longer operating periods and less production time that is lost between relining of the kiln. Thus, the advantages offset their higher costs.

Table 13: Key Facts of Measure – Kiln Shell Heat Loss Reduction

Key Facts of Measure – Kiln Shell Heat Loss Reduction (Improved Refractories)	
Investment Cost:	0.20 EURO/annual tonne clinker capacity
Energy Savings: (Thermal)	0.12 to 0.4 GJ/$t_{clinker}$ (33 to 111 kWh/$t_{clinker}$)
CO_2 Mitigation:	24.6 kg CO_2/$t_{clinker}$ (Price, et al., 2012)
Advantage:	• Heat loss reduction • Improving the reliability of the kiln • Reducing production costs
Disadvantage:	• Structural considerations

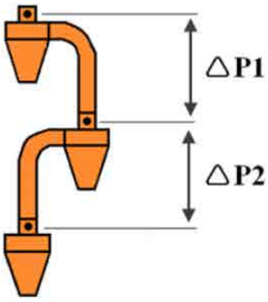
4.6 Low-Pressure Drop Cyclones for Suspension Preheaters

4.6.1 Description of Baseline Situation and Energy Consumption

The cyclone preheaters normally consist of four to six cyclone stages arranged one above the other, in towers 50 to 120 meters high. The exhaust gas from the rotary kiln flows through the different stages from bottom to top. The raw meal, on the other hand, is introduced in the top stage and passes through the cyclone preheater in the opposite direction as the exhaust gas flow and is heated to higher temperatures in each stage.

There are criteria for selecting the number of cyclone preheater stages other than drying the materials. Typical determining factors include construction cost, electricity and fuel price, gas conditioning system, heat exchange efficiency, radiation losses, and pressure drop, the latter one being one of the most important factors affecting the number of cyclone stages. The number of cyclone stages in a preheater system largely determines the system's heat efficiency.

Figure 23: Pressure Drop across One Stage of Cyclones



Source: (Infinity for Cement Equipment, 2021)

Typically, the pressure drop across a 4-stage preheater is 500 to 550 mmwg. Any increase in the number of cyclones results in additional pressure drop, offsetting the gain in fuel efficiency.

4.6.2 Suggested Measures of Improvement

The pressure drop across the cyclone is directly related to the fan power required for operating a cyclonic separator device. Therefore, it is important to measure the pressure drop associated with each inlet velocity.

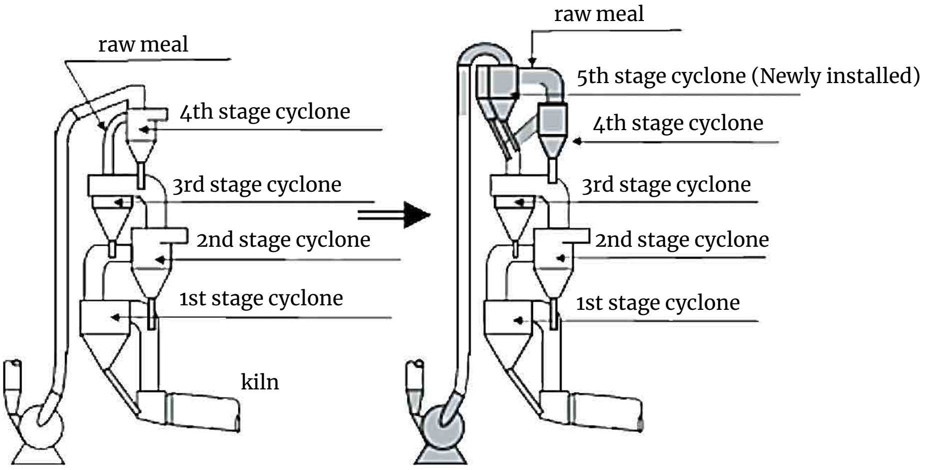
The inlet shape of an ordinary cyclone is revised so that it reduces the inlet wind velocity. This uses the gravity sedimentation effect and reduces the pressure loss while maintaining the dust collection efficiency. Such special inlet shape types are available as axial and horizontal.

The installation of newer cyclones in a plant with lower pressure losses will reduce the power consumption of the kiln exhaust gas fan system. Using cyclones of low-pressure design reduces not only fuel consumption but also specific gas volume, expressed in Nm3/kg clinker. Pressure drops in efficient 6 stages preheaters are comparable to or even less than those in a 4-stage preheater of old designs (see table below). Due to the reduced pressure drop, temperature and reduced gas volume-specific power for preheater fan are also lower when compared to 4 cyclones. Because of this development, it has been possible to increase the number of stages from 4 to 6 without an extra burden in terms of power consumption.

Table 14: Pressure Drop and Energy Consumption with 4 , 5 and 6 Cyclones

Stage	Pressure Drop [mmwg]	Exhaust Gas Temperature [°C]	Fuel Consumption [kWh/kg$_{clinker}$]	Gas Consumption [Nm³/kg$_{clinker}$]	Power Fan [kWh/t$_{clinker}$]
4	280-300	350	0.93	1.65	5.75
5	320-370	300	0.87	1.55	6.05
6	400-450	270	0.81	1.45	6.30

Figure 24: Adding Low-pressure Cyclone



Source: (Infinity for Cement Equipment, 2021))

4.6.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

The installation of newer cyclones with lower pressure losses will reduce the fuel consumption of the kiln exhaust gas fan system in a plant. Depending on the efficiency of the fan, 0.6-0.7 kWh/tclinker can be saved for each 50 mmwg the pressure loss. For older kilns, this amounts to savings of 0.6-1.4 kWh/tonne. Electricity savings of 3 kWh/tclinker and an increase by 3% in capacity have also been reported (Worrell, Kermeli, & Galitsky, 2013).

The investment cost for replacing 3 cyclone stages was estimated by ECRA (2009) at 4.4-5.2 EURO/annual tonne clinker capacity, while in another study (Hollingshead and Venta, 2009), the cost for replacing the inlet and the outer cyclones was estimated at 3 EURO/annual tonne clinker. The replacement of older preheaters with low-pressure drop preheaters makes economic sense, since the preheater tower does not have to be rebuilt (Worrell, Kermeli, & Galitsky, 2013). New cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower.

Table 15: Key Facts of Measure – Low-Pressure Drop Cyclones for Suspension Preheaters

Key Facts of Measure – Low-Pressure Drop Cyclones for Suspension Preheaters	
Investment Cost:	3-5.2 EURO/annual tonne clinker
Energy Savings:	• Thermal: 2.16-5 GJ/$t_{clinker}$ (0.6-1.4 kWh/$t_{clinker}$) • Electricity: 3 kWh/$t_{clinker}$
CO_2 Mitigation:	2-3 kgCO_2/$t_{clinker}$
Advantage:	• Power consumption reduction • Fuel consumption reduction • Increase incapacity
Disadvantage:	• Preheater tower need to modify • Increase overall dust loading

4.7 Oxygen Enrichment Technology

4.7.1 Description of Baseline Situation and Energy Consumption

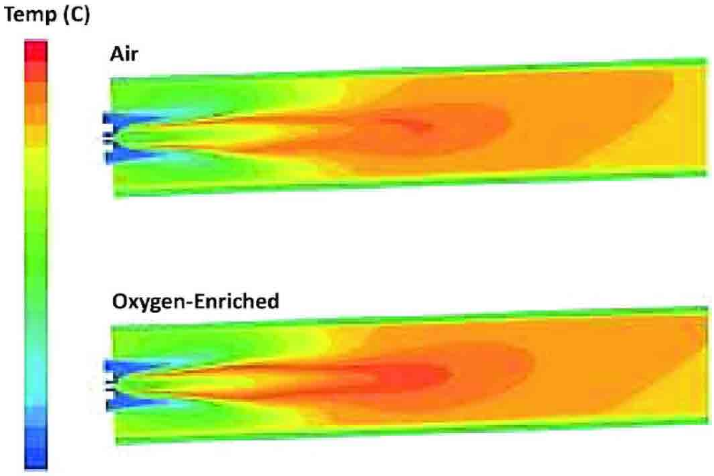
Cement rotary kilns need to reach an extreme combustion temperature. A high flame temperature guarantees normal clinker burning, which is connected with fuel type, fuel supply, kiln body heat loss, and other factors such as the amount of injected oxygen. To keep heat losses in a cement kiln to a minimum, kilns are operated at the lowest reasonable excess oxygen levels.

As oxygen content increases in the primary air system, oxygen molecules come into full contact with combustible and achieve complete combustion. In absence of needed oxygen, the flame temperature decreases, reducing heat transfer from the flame to the clinker, which in turn decreases the clinker's kiln temperature.

4.7.2 Suggested Measures of Improvement

Oxygen enrichment is the process of injecting oxygen (as opposed to air) directly into the combustion zone (or as an adjunct to the combustion air stream) to increase the efficiency of combustion. This technology has been used by industries using high-temperature combustion processes. Oxygen increases the combustion of fuels and improves the burning zone. Further, by using this technique, the kiln stability increases, and emissions decrease. By increasing the oxygen concentration of combustion air through the addition of relatively pure oxygen, flame temperatures rise, heat transfer rates improve, and overall combustion efficiency increases.

Figure 25: A Flame Profile in a Kiln with and without Oxygen Enrichment



Source: (Mittal, Saxena, & Mohapatra, 2020)

Oxygen enrichment increases the temperature in the hottest zone around the core of the flame, while the temperature at the walls of the kiln remains similar to that of the conventional air combustion flame (s. figure above). This translates into increased production and reduced emissions. According to the reports and experience with oxygen, the injection has demonstrated an increase of up to 25 % in the production, reduced specific dust losses, and improved kiln stability, as evidenced by clinker quality and kiln coating (International Finance Corporation (IFC), 2017).

Figure 26: Production Gains Achieved in Different Plants Using Oxygen Enrichment Technology

Company	Base Production (tons per day)	New Production (ton per day)	% Increase
A	1,300	1,490	15
B	4,000	4,360	9
C	3,800	5,000	32
D	2,000	2,140	7

Source: (International Finance Corporation (IFC), 2017))

Oxygen enrichment can also be used for improving stable and consistent combustion of alternative fuels co-processing (Chapter 4.3) with low heating value and larger particle size. The injection of oxygen into the flame source is effective for low-quality alternative fuels as it enables quicker heat-up, fuel devolatilization, and fuel firing.

Figure 27: Production Gains Achieved in Different Plants Using Oxygen Enrichment Technology

	Plant							
	A	B	C	D	E	F	G	H
% alternative fuel usagewithout oxygen	45.4	31.1	45.9	44.3	42.8	43.9	60.5	27.0
% alternative fuel usagewithout oxygen	72.9	52.4	69.3	65.6	77.3	58.3	67.0	40.7
% reduction in fossil fuel	-50.0	-25.9	-40.0	-36.0	-57.5	-25.0	-10.8	-22.0
CO$_2$e savings(tons per year)b	13,500.0	8,100.0	10,800.0	9,720.0	34,500.0	10,800.0	3,780.0	11,880.0

a. Production rates were held constant except for Plant G where there was %4 production increase with oxygen.

b. Results are from recent installations (since2009).

c. Carbon dioxide equivalent (CO$_2$e)savings at Plant E were greater due to the substitution of biomass fuels for fossil fuel.

Source: (International Finance Corporation (IFC), 2017)

4.7.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

This measure is useful for plants that need additional capacity or want to maximize alternative fuel use. It requires an oxygen source and dedicated air separation plants, which are capital intensive. Increased electricity use for oxygen production must be included in the plant energy balance.

Thermal energy consumption can be reduced by 100 to 200 MJ/$t_{clinker}$ (27 to 55 kWh/tclinker). Electricity consumption can increase by 10 to 35 kWh/tclinker due to oxygen production (International Finance Corporation (IFC), 2017).

While this technology reduces direct CO2 emissions by 10 to 20 kg/tclinker due to reduced fuel consumption, the indirect emissions are estimated to rise by 15 to 25 kg/t clinker due to increased electricity use (Institute for Industrial Productivity, 2021). Actual net effects depend on the electricity source.

The economics of this technology are determined by power price and investment costs. For a plant with a capacity of 2 million tonnes per year and assuming an air separation unit, new installation and retrofit costs are estimated to be 6 million EURO to 12 million EURO.

Table 16: Key Facts of Measure – Oxygen Enrichment Technology

Key Facts of Measure – Oxygen Enrichment Technology	
Investment Cost:	6 million EURO to 12 million EURO
Energy Savings:	● Thermal saving 97-198 MJ (27 to 55 kWh/$t_{clinker}$) ● Electricity increases by 10 to 35 kWh/$t_{clinker}$
CO_2 Mitigation: (direct)	10 to 20 kg/$t_{clinker}$
Advantage:	● Energy saving ● Maximizing alternative fuel use ● Improving the stability of combustion
Disadvantage:	● High investment cost ● Air separation plants are needed ● Increase in electricity demand ● Increase in indirect emissions due to increase in electricity use

4.8 Optimized Waste Heat Recovery (WHR) in Clinker Cooler

4.8.1 Description of Baseline Situation and Energy Consumption

The clinker cooler is an important part of the kiln system. It affects performance and the economics of clinker production. The cooler has two tasks: to recover as much heat as possible from the hot (1450 °C) clinker and return it to the process, and to reduce the clinker temperature to a level suitable for the next process steps.

There are two main types of coolers: rotary and grate. In the grate cooler, the clinker is transported over a reciprocating grate through which air flows perpendicular to the flow of the clinker. In the rotary cooler, the clinker is cooled in a counter-current air stream.

It is common that the excess heat from the cooler is used for heating the secondary air for the kiln combustion process and sometimes also tertiary air for the pre calciner. Grate coolers use electric fans and excess air. The highest temperature portion of the remaining air can be used as tertiary air for the pre calciner. Rotary coolers do not need combustion air fans and use little excess air, resulting in relatively lower heat losses (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013) , (Worrell, Kermeli, & Galitsky, 2013).

In dry process cement plants, nearly 40 % of the total heat input is available as waste heat from the exit gases of the preheater and clinker cooler. The quantity of heat from the clinker cooler ranges from 330 to 540 MJ/$t_{clinker}$ (91-150 kWh/tclinker) from the exhaust air of the cooler. The table below summarizes the heat available in different generations of grate coolers. Exhaust air temperatures from the clinker cooler range from 250 to 340°C depending on cooler configuration and recuperation efficiency (International Finance Corporation (IFC), 2018).

Table 17: Available Heat for Grate Clinker Coolers

Parameter	Unit	1st Generation	2nd Generation	3nd Generation
Grate Plate Type	N/A	Verical Aeration wtih Holes in Plate	Horizontal Aeration	Horizontal Aeration
Cooling Air Input	$Nm^3/kg_{clinker}$	2.0-2.5	1.8-2.0	1.4-1.5
Exhaust Air volume	$Nm^3/kg_{clinker}$	1.0-1.5	0.9-1.2	0.7-0.9
Heat Available in Exhaust	$GJ/Tonne_{clinker}$ (kcal/kg)	0.419-0.520 (100-120)	0.335-0.419 (80-100)	0.293-0.335 (70-80)
	GJ/hr for 1MTPA* (Mkcal/hr)	52.3-62.8 (12.5-15.0)	41.9-52.3 (10.0-12.5)	36.6-41.9 (8.8-10.0)
Recuperation Efficiency	%	<65	<70	>73

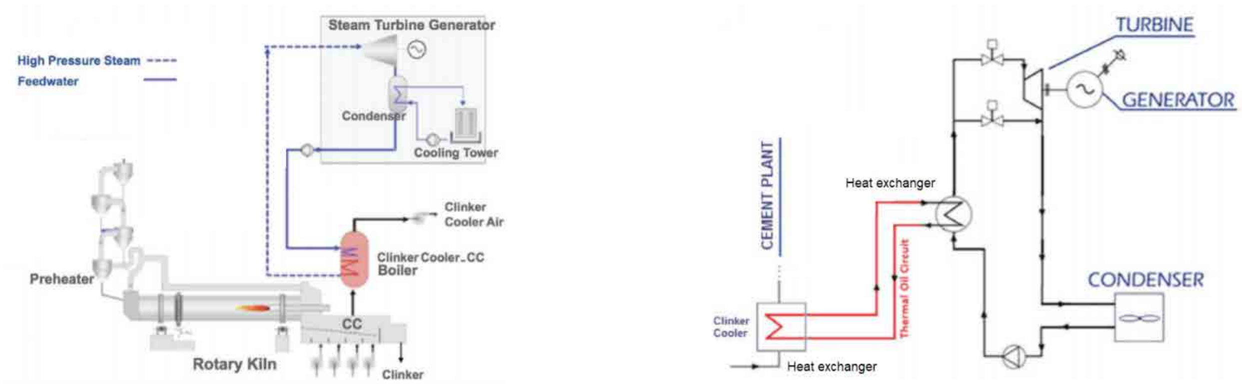
MTPA – million metric tonnes per year

4.8.2 Suggested Measures of Improvement

Typically, cement plants do not have significant low-temperature heating requirements, hence waste heat recovery projects are mainly used for power generation. Waste heat recovery can provide up to 30 % of a cement plant's overall electricity needs.

Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle (RC). This thermodynamic cycle consists of a heat source (boiler) that converts a liquid working fluid to high-pressure vapor (steam, in a power station) that is then expanded through a turbogenerator producing power. Low-pressure vapor exhausted from the turbogenerator is condensed back to a liquid state, with condensate from the condenser returned to the boiler feedwater pump to continue the cycle. Waste heat recovery RC can be based on steam or an organic compound used as the working fluid. Steam Rankine Cycle (SRC) and Organic Rankine Cycle (ORC) are the most common Waste heat recovery system in cement.

Figure 28: Waste Heat Recovery System. Left using Steam Rankine Cycle (SRC), right using Organic Rankine Cycle (ORC),



Source: Adapted from (International Finance Corporation (IFC), 2018)

As it can be seen in Figure 28-Left working fluid, water in SRC is first pumped to elevated pressure before entering the boiler. In SRC, water is vaporized by the hot exhaust from the clinker cooler boiler and then expanded to lower temperature and pressure in a turbine. This produces mechanical power that drives an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where the expanded vapor is condensed to low-pressure liquid and returned to the feedwater pump and boiler (International Finance Corporation (IFC), 2018).

ORC systems are designed with two heat transfer stages (Figure 28-Right). The first stage transfers heat from the waste gases to an intermediate heat transfer fluid (for example, thermal transfer oil). The second stage transfers heat from the intermediate heat transfer fluid to the organic working fluid. ORC systems typically use a high-molecular-mass organic working fluid such as butane or pentane that has a lower boiling point, higher vapor pressure, higher molecular mass, and higher mass flow compared to water.

The electric efficiency of a Steam Rankine Cycle can reach 45 to 46 % in modern power plants. The relatively low-temperature level of heat from the cooler (250 to 340 °C) limits the efficiency of waste heat recovery systems in cement kilns to a maximum of 18 to 25 %. ORC systems can be used for waste heat sources as low as 150 °C and have higher turbine efficiencies than those offered by a steam system.

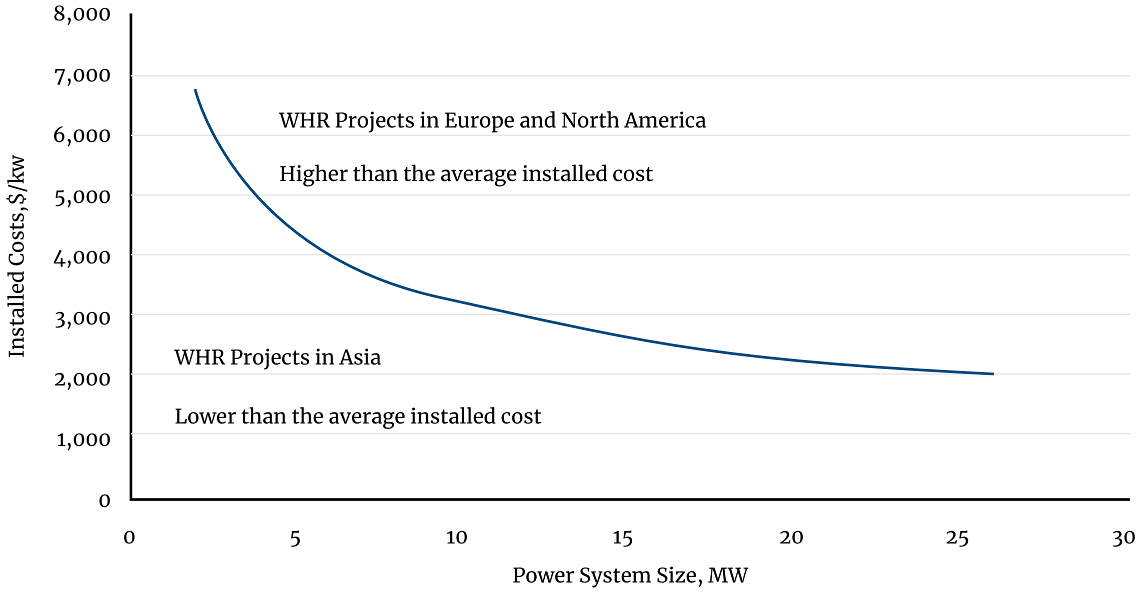
4.8.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

The economics of waste heat power generation depends on several site-specific and project-specific factors, including the following:

- The amount of heat available in waste gases and conditions of such gases, which determine the WHR system's size, potentially its technology, and its overall generation efficiency.
- The capital cost of the heat recovery system, which generally depends on size, the technology used, and equipment supplier.
- System installation costs (design, engineering, construction, commissioning, and training) depend on the installation size, technology, complexity, supplier, and degree of local content.
- System operating and maintenance costs are affected by the size, technology, site-specific operational constraints, or requirements.
- Operating hours of the kiln and availability of the heat recovery system.
- The net power output of the WHR system.
- Availability of space close to the preheater, cooler, and air-cooled condensers.

The figure below shows industry estimations regarding total average[17] installed costs for cement WHR projects on a USD/kWe (1 USD = 0,82 EURO) basis and illustrates that costs depend heavily on project size (MW), local cost variations (region of the installation), and type of technology (systems lower than 2 to 3 MW tend to be ORC systems). Total capital cost (equipment and installation) is strongly influenced by size – smaller WHR systems have a higher cost per kW of generation capacity. Hence, total installed costs for WHR systems range from 5,700 EURO/kWe for 2-MW systems (ORC) in Europe to 1,600 EURO/kWe for 25-MW systems (steam) in Asia.

Figure 29: WHR Installed Costs, USD/kWe



Source: (International Finance Corporation (IFC), 2018)

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[17] The curve shows the average installed costs. Typical projects in Europe and North America have higher installed costs, WHR projects in Asia rather lower installed costs than the average.

Table 18: Key Facts of Measure – Optimized Waste Heat Recovery (WHR) in Clinker Cooler

Key Facts of Measure – Optimized Waste Heat Recovery (WHR) in Clinker Cooler	
Investment Cost:	See Figure 29
Energy Savings: (Thermal and Electricity)	Strongly depends on the plant and WHR system size.
CO_2 Mitigation:	31.7 $kg_{CO2}/t_{clinker}$ (Price, et al., 2012)
Advantage:	● Increased independence from energy costs ● Reduction of CO_2 emissions
Disadvantage:	● High investment cost

4.9 Vertical Roller Mills for Finish Grinding

4.9.1 Description of Baseline Situation and Energy Consumption

The last step in cement production is finish grinding, which accounts for about 40-45% of overall electricity consumption of the mill and about 51 kWh/tcement. Cement grinding influences cement properties (e. g. strength, water requirements) significantly. In the recent past, cement products have shifted towards cements of higher strength classes and also higher product fineness. This change has also led to increasing specific energy requirements for cement grinding processes. (Ausfelder Florian, 2018).

Clinker is finely ground alone (possibly with up to 5% secondary components) or together with other main components. To regulate the solidification, gypsum stone or a gypsum-anhydrite mixture is added to the ground material. When applying joint fine grinding, the grain size distributions of the individual components cannot be separately influenced. Separate grinding and subsequent mixing can also be useful for optimal cement production due to the different grindability of the cement raw materials.

In principle, there are three types of mills:

- **Ball mills** (crushing of the cement raw materials by grinding balls)
- **Material bed roller mills** (crushing of the material to be ground by two mutually rotating grinding rollers) or
- **Vertical roller mills** (grinding of the material to be ground by rolling on a rotating grinding table) are used for grinding the cement. (Diethelm Bosold, 2017).

Ball mills are still the most commonly used type of mills, as they are relatively easy to operate and a reliable technology. They allow a wide grain distribution and thus produce favourable processing properties. These mills normally have tube diameters of up to 6 m and tube lengths of up to 20 m. Furthermore, mineral additions with certain moisture content can be, to a limited extent, dried by passing hot gases to the mill and using the heat from the grinding process. (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013).

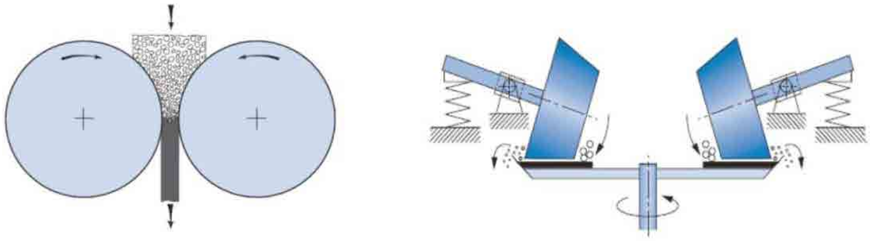
However, compared with other mill types, ball mills have a higher specific energy consumption and rank last in energy efficiency.

4.9.2 Suggested Measures of Improvement

Energy saving potentials in the grinding process can be achieved via **process optimization** (including optimization of classifiers, adaptation of process variables such as circulation number or circulation speed of the classifier or the use of grinding aids) and via the replacement of existing ball mills by **more efficient mills**. (ALLPLAN GmbH, 2010). This chapter focuses on efficient mills.

The following chart shows the concept of **ball mills** and **vertical roller mills**:

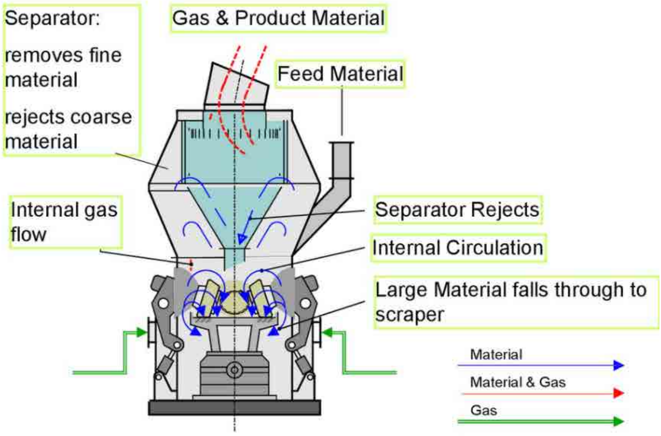
Figure 30: Ball Mills (left) and Vertical Roller Mills (right)



Source: (ALLPLAN GmbH, 2010)

Vertical roller mills (see figure below) consist of two to four grinding rollers supported on hinged arms and riding on a horizontal grinding table or grinding bowl. These types of mills are suited especially for simultaneous grinding and drying of cement raw materials or slag since vertical roller mills can handle relatively high moisture contents in the mill feeds. The transition time for materials through the mill is short enough to prevent pre hydration of the cement clinker, e. g. in the case of slag cement grinding. (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013)

Figure 31: Vertical Roller Mills

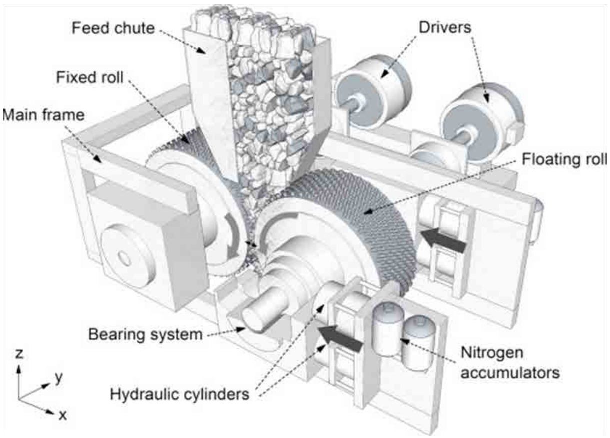


Source: https://en.ppt-online.org/825491

Vertical roller mills showed initial problems with vibration in the mill, wear of the grinding roller and grinding disc, and product quality issues in finish grinding. Main issues relate to resulting particle size distribution of the cement depending on the specific system. According to more recent sources, these issues have been generally solved, but maintenance and spare-part management remain main considerations for this mill type. (IFC, 2017).

Another type, the high-pressure twin roller mill (also Gutbett Roller Mill) – see the figure below - works with high pressure (up to 3500 bar) and is often used for expanding the capacity of existing mills. (IFC, 2017). According to the BAT document (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013) this type still needs a comparatively high degree of maintenance. High pressure twin roller mills are often used in conjunction with ball mills.

Figure 32: High Pressure/Gutbett Roller Mills



Source: (Barrios Gabriel K.P., 2016)

Grain sizes up to 4,500 to 5,500 Blaine in vertical roller mills and high-pressure grinding rolls can be achieved. The following table summarizes the characteristics of different mill types:

Table 19: Comparison of Mill Types

Grinding Process	Energy Consumption	Maintenance Requirements	Drying Capacity	Suitability for Grinding to Great Fineness
Ball mill	100%	Minor	Average	Good
Gutbett roller mill	65 to 50%	Minor to major	Low (')	Average
Vertical roller mill	75 to 70%	Average	High	Average
(')Drying in classifier *Source: [60, VDI 2094 Germany, 2003] [76, Germany, 2006]*				

Source: (Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013)

Considerable energy savings can be achieved by combining or replacing ball mills with more efficient processes. The most common are:

- **Pre-grinding** is done in Vertical Roller Press, finish grinding in classic ball mill- classifier
- **Hybrid-grinding**: part of the grinding is taken over by the ball mill, part by the vertical roller mill.
- **Combined grinding**: The fresh material is placed on the roller press; after comminution in this aggregate, the fine material produced in the first comminution step is separated off via the sifter of the roller press. This "partially finished" product from the primary grinding circuit is then fed to the ball mill, which can be operated as a closed grinding-classifying circuit or as a continuous mill. Through this secondary grinding, the intermediate product from the roller press is then ground to the desired product fineness. The coarse classifier of the primary circuit is fed back to the roller press together with the fresh material.
- **Separate grinding** of different cement input fractions with different mills can take into account the specific properties of various cement constituents. Joint grinding of the components of CEM-III cements is always problematic due to different grindability of cement clinker and blast furnace slag. Since the vertical roller mill is particularly well suited for mill-drying of substances with high feed moisture, the installation of such a mill can be particularly useful when larger quantities of slag are processed

Each of the processes described above, based on the Austrian experience, can lead to electricity savings up to 10% (ALLPLAN GmbH, 2010).[18]

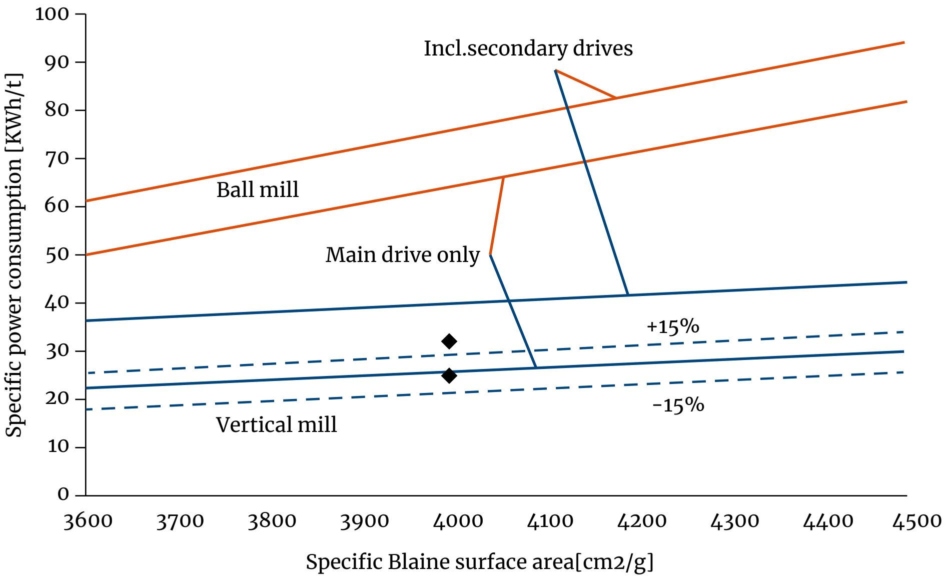
Apart from improvements at existing mills (as described above) also the complete **replacement of ball mill** (replacement of ball mills by vertical roller mills with an integral separator) is possible, which leads to electricity savings in the range of 30-40%.

4.9.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

In various sources[19], energy saving potentials of roller mills compared to ball mills are estimated to be in the range of 30-40% of electricity consumption, i.e. 10-15 kWh/tcement. (Institute for Industrial Productivity, 2021) A detailed evaluation of specific energy consumption depending on the specific surface according to Blaine (depicting the fineness of grinding) and differentiating between the main and auxiliary drives is depicted below.

For the production of one tonne of finished product (with a grinding fineness of 4000 cm2/g according to Blaine), a specific energy requirement of 25 kWh/tproduct was determined for the main drive with freshly welded grinding rollers and an intact grinding table surface. This value can rise to 30 kWh/t with increasing wear. If the auxiliary drives (including among others blowers, the internal classifier) are included in the performance evaluation, the specific energy requirement increases to approx. 40 kWh/t. In comparison, the specific energy requirement of ball mills with/without auxiliary drives amounts to 60/75kWh/t respectively.

Figure 33: Specific Energy Consumption of Ball Mills and Vertical Mills (kWh/t)



Source: (M. Pohl, C. Obry Buzzi Unicem S.p.A., & K.-H. Zysk, 2012)

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[18] Other sources point at considerably higher savings e. g. for the combined use of pressure rolls and ball mills in the range of 15-30% compared to a traditional ball mill. (IFC 2017).

[19] (Institute for Industrial Productivity, 2021), (M. Pohl, C. Obry Buzzi Unicem S.p.A., & K.-H. Zysk, 2012), (Schorcht, Kourti, Scalet, Roudier, & Sancho, Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide, 2013)

Table 20: Key Facts of Measure – Vertical Roller Mills for Finish Grinding

Key Facts of Measure – Vertical Roller Mills for Finish Grinding	
Investment Cost:	2.5-8 USD/$t_{\text{cement (annual)}}$
Energy Savings: (Electricity)	• Replacement: 30-40% (electricity), 10-15 kWh/t_{cement} • combined use with ball mills: appr. 10%, 5 kWh/t_{cement}
CO_2 Mitigation:	Replacement: 7.9 to 19 kg/t_{cement}
Advantage:	• Considerable energy savings • Suitable also for slag processing
Disadvantage:	• Formerly: instability of material bed, vibration in the mill, serious wear of grinding roller and grinding disc • Product quality issues mainly relating to resulting particle size distribution of the cement • Increased maintenance efforts

4.10 Outlook on Further Developments

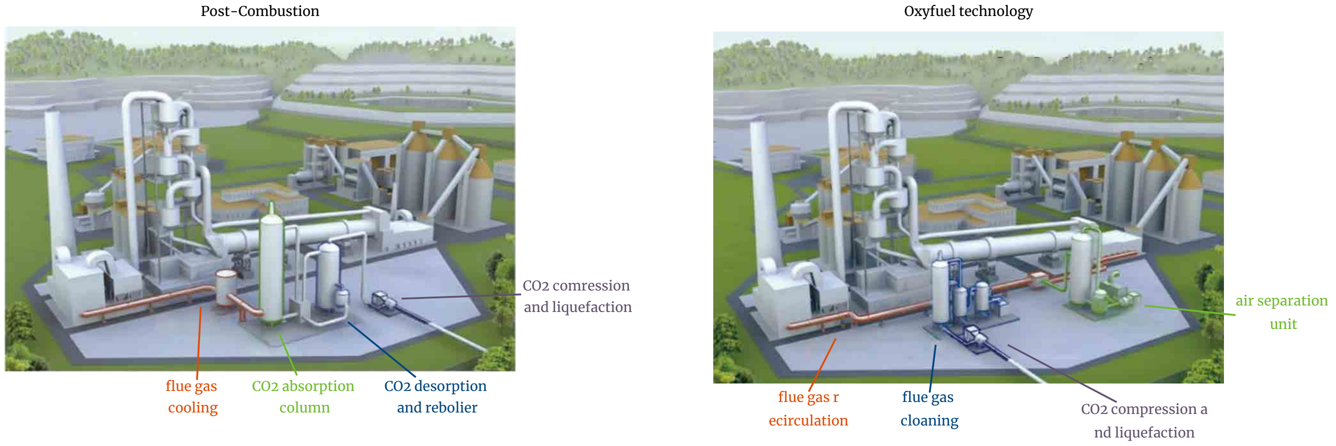
Due to the particularly large share of process-related emissions of cement production, the greatest challenge in the upcoming years is certainly the reduction of CO2 emissions in cement production. Ongoing efforts of cement manufacturers have resulted in increasing energy efficiency in the production process and the development of clinker-efficient cements with lower CO2 footprint than classic Portland cements: The average clinker content in the cement was reduced to 71 % by expanded use of composite and blast furnace cements. Ultimately, however, it is clear that the **raw material-related process emissions in cement production limit** the reduction in CO2 emissions. (Verein Deutscher Zementwerke, Hrsg., 2020).

Given this, the European Cement Research Academy (ECRA), cement manufacturers, plant engineers, universities and scientific institutions have been researching techniques for further CO2 reduction.

CO2 can be captured at the chimney of rotary kiln plants in cement works in order to either store it for the long term (**carbon capture and storage**) or use it for another purpose later (**carbon capture and utilization**). After conducting many different studies and dedicated research projects, the European cement industry is currently testing CO2 capture on an industrial scale, which is expected to deliver significant reductions in process-related greenhouse gas emissions.

Two major technologies are currently being investigated: post- combustion and oxy-fuel technology.

Figure 34: Scheme of CO_2-Post Combustion and Oxyfuel Technology



Source: (Schneider, 2018)

The major characteristics are:

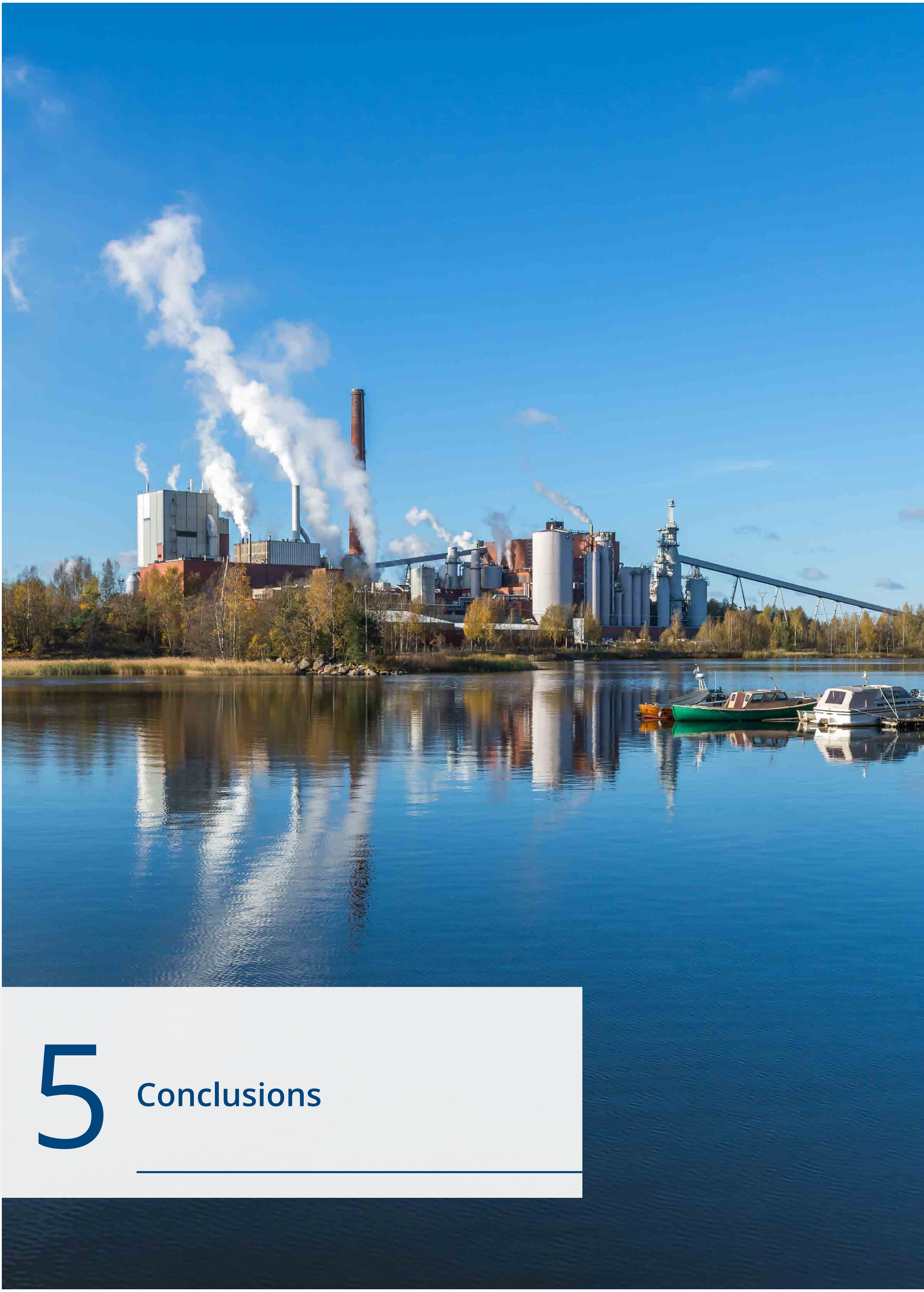
Post Combustion: (e.g., see Norcem Brevig Project, Heidelberg Cement https://www.norcem.no/en/CCS)

- Tail-end separation of CO2 from flue gas by e.g. chemical absorption, adsorption, membranes or Ca-looping
- Very energy-intensive technology.

Oxyfuel Technology (e.g. see pilot project Lafarge Retznei in Austria):

- Combustion with pure oxygen instead of air in combination with flue gas recirculation to increase the CO2 concentration.
- Requires process and design adaptations. (Schneider, 2018)

The disadvantages are that the process is still extremely energy-intensive and expensive and questions relating to CO_2 transportation, long term storage or reuse have not been answered yet..



5

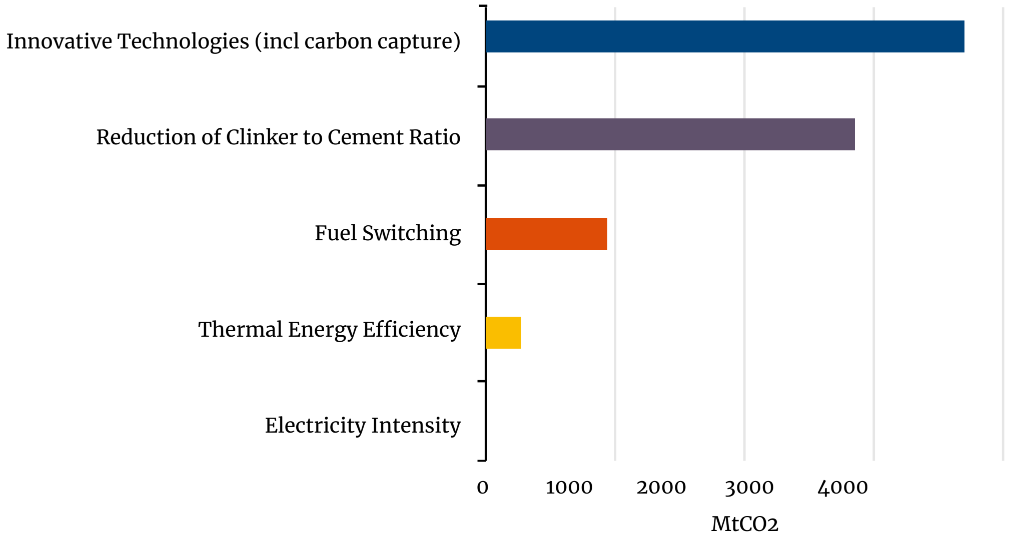
Conclusions

Cement production is a very energy-intensive process. Throughout the whole production process, there is a wide range of measures available to improve energy and resource efficiency of the mills and to reduce CO2 emissions.

However, due to the large share of process emissions, the CO2 reduction potential via optimization of thermal and electrical efficiency is limited. Further potential lies in product changes (adaptation of the clinker-cement ratio) and carbon capture and storage technologies.

In the long run, up to 48% of CO2 reduction are expected to result from Carbon Capture technologies, followed by 37% of emissions reductions from reducing the clinker to cement ratio. Fuel switching and thermal energy efficiency contributions only play a minor role (IEA, Technology Roadmap Low-Carbon Transition in the Cement Industry, Low-Carbon Transition in the Cement Industry, 2018) .[20]

Figure 35: Contributions to Global CO2 Reductions



NOTE: Cumulative CO2 emissions reductions refer to the period from 2020 and based on the low variability case of the scenarios.

Adapted from: (IEA, Technology Roadmap Low-Carbon Transition in the Cement Industry, Low-Carbon Transition in the Cement Industry , 2018)

The following table summarizes the most promising measures which are either easy-to-implement or have a comparatively high potential. Details are presented in the respective sub-chapters of the report.

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[20] Roadmap vision for 2050, compared to the RFS (Reference Technology Scenario) by 2050

Table 21: Summary of Measures

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (Thermal and Electricity)	CO_2 Mitigation	Advantage	Disadvantage
High Efficiency Separators and Classifiers	1-2.5 EURO/$t_{product}$	2.3-4.5 kWh/$t_{product}$ (Electricity)	1.1-2.3 kg CO_2/$t_{product}$	• Reduction of electricity consumption • Increase of throughput • Improved product quality	• Difficulty to reach optimum seal system • Physical layout of the grinding system must allow retrofitting
Blended Cement Alternatives	• 0-6 million EUR/$t_{clinker}$ • Operational costs increase by 0-4.2 EUR/$t_{clinker}$	• 100-400 MJ/$t_{clinker}$ (30-110 kWh/$t_{clinker}$) decrease of thermal energy demand • 0-3 kWh/$t_{clinker}$ increase of electrical energy demand	100 kg CO_2/$t_{clinker}$ (10-15% replacement of raw material by GBPS)	• Considerable reduction of thermal energy demand and process emissions • Partly use of waste	• Not all types of cement are suitable for all types of applications • Additional process steps required (grinding, blending), additional quality assurance • Difference in local availability of alternative raw materials (quality/quantity) • Reduced availability of GBFS and fly ash in the future due to expected production changes
Alternative Fuels Co-Processing	• 5-15 mEUR (retrofit; clinker capacity 2 mt/a) • reduction of operational cost by 2-2.5 EUR/$t_{clinker}$	• Reduction of fossil fuel consumption • Increase of overall thermal energy demand: by 200-300 MJ/$t_{clinker}$ • Increase of overall electric energy demand: by 2-4 kWh/$t_{clinker}$	• 1.42-1.8 t CO_2/t RDF (substitution of coal) • 30-50 kg CO_2/$t_{clinker}$	• Reduction of fossil fuel consumption • Higher material efficiency, less waste disposal	• Partly higher thermal energy demand compared to fossil fuels • Additional process steps for fuel preparation (drying, grinding) • Potential operational problems at high substitution rates • Hard to implement when framework conditions are not yet in place (legislation, waste collection/availability and monitoring, social acceptance)

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (Thermal and Electricity)	CO_2 Mitigation	Advantage	Disadvantage
Process Control Optimization in Clinker Making	125.000 EUR (plant with capacity of 4,500 tonne per day)	• Thermal: 2.5-10 %, 32 kWh/$t_{clinker}$ (Spec. potential savings) • Electrical: 2 kWh/$t_{clinker}$	2.9-5.9 kg CO_2/$t_{clinker}$	• Improve heat recovery • Improve material throughput • Reliable control of free lime content in the clinker • Decrease fuel consumption • Decrease refractory consumption • Lower maintenance costs	A high educational level of operators and staff is critical for process control and optimization.
Low-Pressure Drop Cyclones for Suspension Preheaters	3-5.2 EUR/annual tonne clinker	• Thermal: 2.16-5 GJ/$t_{clinker}$ (0.6-1.4 kWh/$t_{clinker}$) • Electricity: 3 kWh/$t_{clinker}$	2-3 kg CO_2/t_{cement}	• Power consumption reduction • Fuel consumption reduction • Increase incapacity	• Preheater tower need to modify • Increase overall dust loading
Oxygen Enrichment Technology	6 million EURO to 12 million EURO	• Thermal saving 97-198 MJ (27 to 55 kWh/$t_{clinker}$) • Electricity increases by 10 to 35 kWh/$t_{clinker}$	10 to 20 kg/$t_{clinker}$	• Energy saving • Maximizing alternative fuel use • Improving the stability of combustion	• High investment cost • Air separation plants are needed • Increase in electricity demand • Increase in indirect emissions due to increase in electricity use
Optimized Waste Heat Recovery (WHR) in Clinker Cooler	See Figure 29	Strongly depends on the plant and WHR system size.	31.7 kg CO_2/$t_{clinker}$	• Increased independence from energy costs • Reduction of CO_2 emissions	High investment cost
Vertical Roller Mills for Finish Grinding	2.5-8 USD/t_{cement} (annual)	• Replacement: 30-40% (electricity), 10-15 kWh/t_{cement} • combined use with ball mills: appr. 10%, 5 kWh/t_{cement}	Replacement: 7.9 to 19 kg/t_{cement}	• Considerable energy savings • Suitable also for slag processing	• Formerly: instability of material bed, vibration in the mill, serious wear of grinding roller and grinding disc • Product quality issues mainly relating to resulting particle size distribution of the cement • Increased maintenance efforts

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