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Technical Guidelines on
Energy Efficiency in Major Energy-Consuming Sectors

Energy Efficiency in the Ceramics Industry

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Imprint

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This report is the third 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 major global challenges, we have seen substantial progress 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 ceramics industry is an energy-intensive sector, with a unit energy consumption of up to 14 MWh per tonne of product for technical ceramics. Energy consumption accounts for up to 30% of a ceramic product's total production costs. It will require coordinated efforts to address the challenges of decarbonizing the ceramics sector, including process and product optimization, energy conservation, electrification of key processes, 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 third 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 ceramics 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 China (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.

Martin Hofmann

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Content

List of Figures

List of Tables

Abbreviations

BAT	Best Available Technology
BM	Benchmark
BREF	Best Available Technologies Reference Documents
CaO	Calcium Oxide
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
Cerame-Unie	European Ceramic Industry Association
DEEDS	Dialogue on European Decarbonization Strategies
EEA	European Environment Agency
ETS	Emissions Trading System
EU	European Union
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
Mt	Million tonne
Mg	Mega-Gramm (identical to one tonne)
MWh	Megawatt hour
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
ODEX	Objective of the Energy Efficiency Index
SIDBI	Small Industries Development Bank of India
toe	Ton oil equivalent
TFC	Total Final Consumption
UNEP	United Nations Environment Programme
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 t**o 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 and 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 **ceramics 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 ceramics in Europe ranges from less than 1 MWh (brick tiles) to 14 MWh (technical ceramics), which shows the wide range of products subsumed under the term "ceramics". Thus, all discussions of average figures and saving potentials have to be treated with caution. After considerable energy efficiency improvements in the 1990s, the current developments rather point at relatively small-scale improvements although there is still a potential for continuous improvement actions including process optimisation in general, energy management, changes in the design and in the raw materials used and changes in the kilns. In order to further reduce CO_2 emissions, further efforts are required. In this respect, European ceramic producers increasingly use alternative energy sources including cogeneration (especially in Italy, Portugal and Spain). Promising – however currently not yet economical – options also include CCS and the replacement of natural gas by syngas from biogas or waste.

This guideline comprises all process steps performed at a given ceramic mill, including raw material preparation, drying, firing and final preparation. The sub-process with the **highest relevance for energy consumption** is the firing process, requiring approximately 60% of overall energy input.

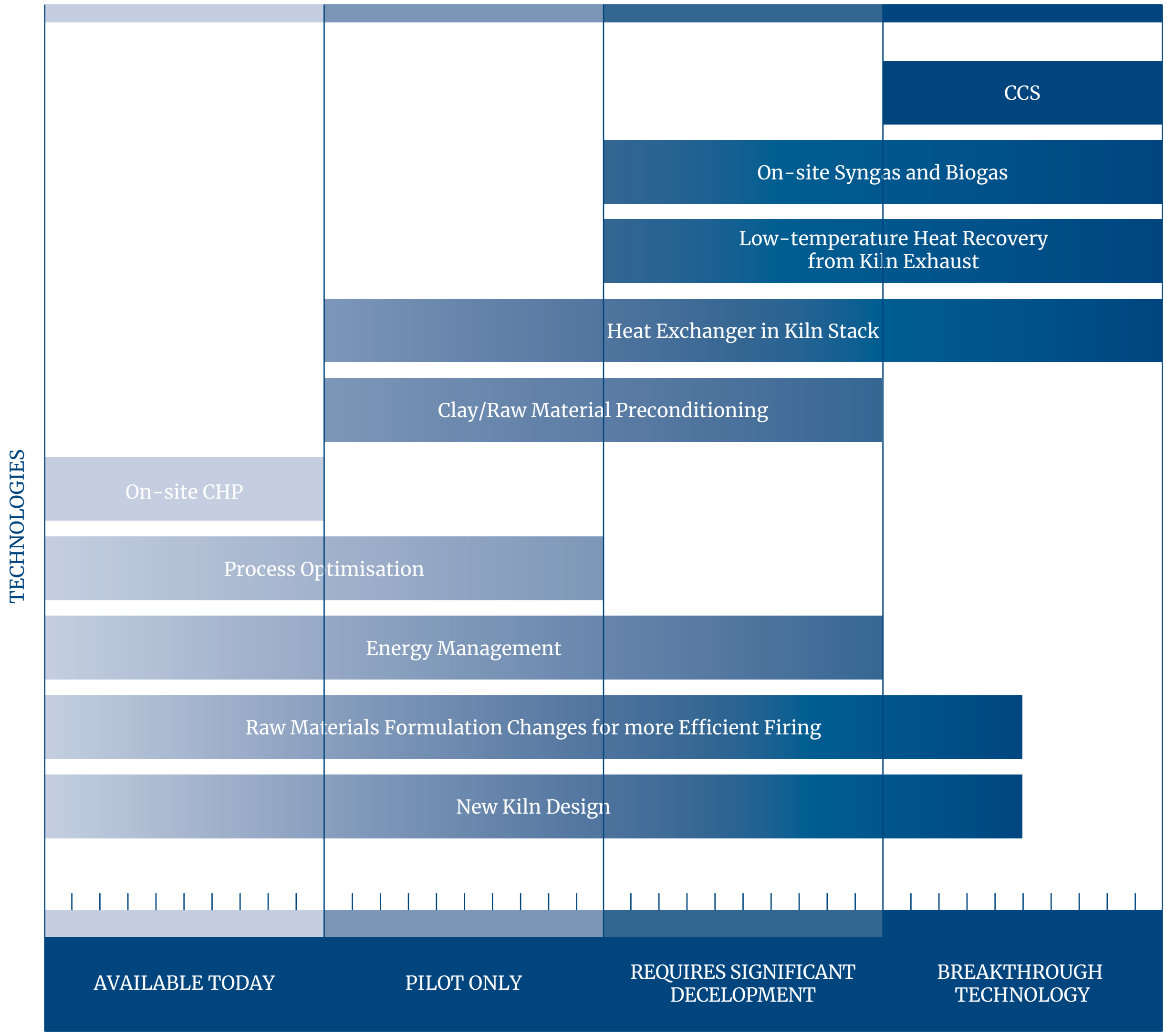
The following energy efficiency measures were identified as the most promising ones and are described in detail in this guideline.

- Use of dry route for raw material preparation
- Improvements at ceramic design
- Airless drying
- Controlled dehumidification
- Exhaust air recirculation in spray dryers
- Drying air preheating
- High-efficiency burners
- Low thermal mass kiln cars and furniture
- Electric kiln and drying
- Microwave assisted firing and drying

Evaluating energy efficiency potentials in terms of changing final energy consumption (electricity and thermal energy) must always be seen in close connection with relevance to GHG reduction. This means that the actual GHG reduction impact strongly depends on the actual fuel replaced and the energy source used for electricity production. This fact especially refers to all fuel switch projects and in the case of ceramics sector to the measure of replacing currently used kilns by electric kilns. Currently, switching to electric kilns leads to a negative CO_2 balance. However, the result can change considerably with low emission electricity sources.

Apart from currently established technologies and CO_2 abatement strategies such as process optimisation and adaptation of raw materials, much additional effort is required to achieve large scale decarbonisation. In the long run, major contributions to CO_2 reduction are expected from carbon capture technologies and from the use of on-site syngas and biogas – as it is shown in the below chart (CeramUnie, 2012).

Figure 1: Contributions to Global CO_2 Reductions

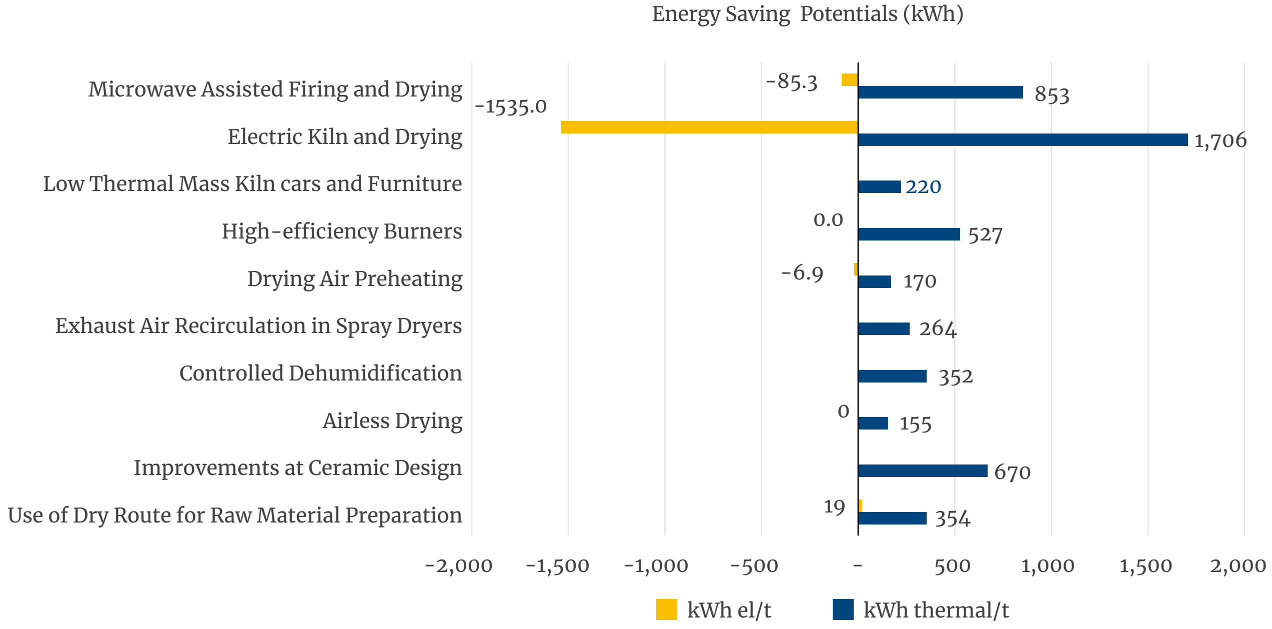


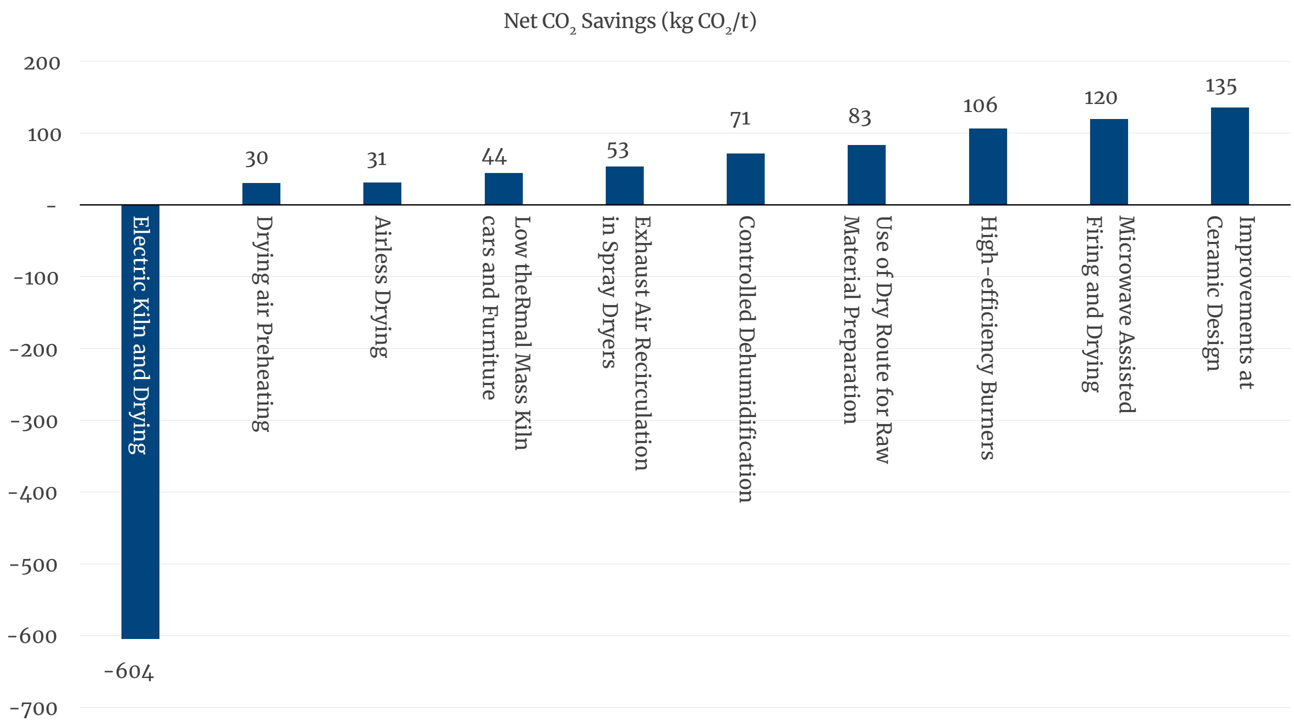
Source: (CeramUnie, 2012)

Due to the heterogenic ceramics sector, energy and CO_2 savings are calculated based on specific assumptions (shown at the respective section) and – if not otherwise specified – on IPCC emission factors for gas (0.202 t CO_2/MWh), coal (0.335 t CO_2/MWh) as well as on the Chinese average grid emission factor of 0.618 t CO_2/MWh taken from the IGES database. (https://www.iges.or.jp/en/pub/list-grid-emission-factor/en)

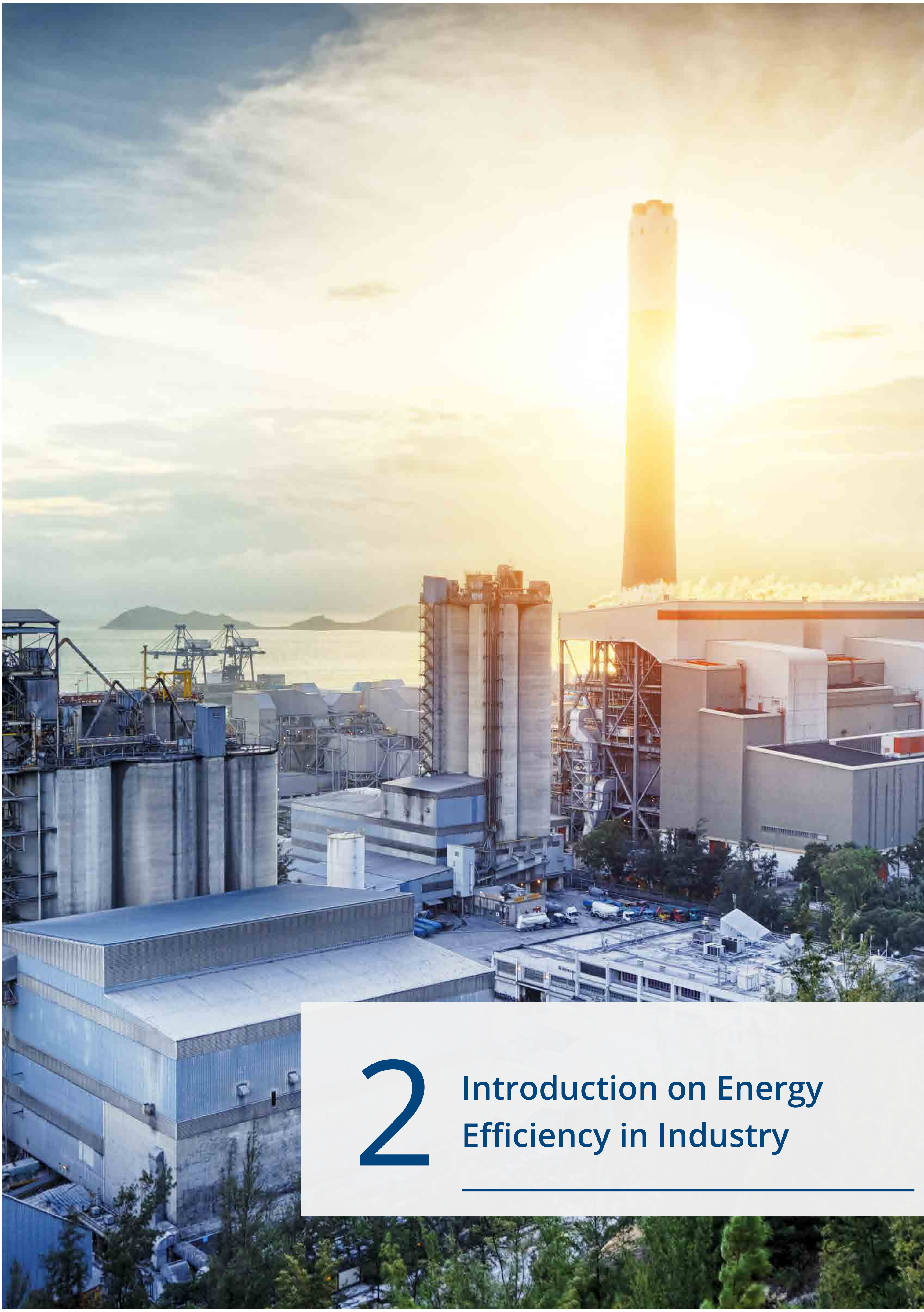
The following charts summarize the expectable energy savings and resulting net CO_2 savings[1]:

Figure 2: Energy and CO_2 Saving Potentials of Selected Measures





[1] Comment: due to the large range of unit energy consumption per subsector it is advisable rather to consider percentage savings given in the report than referring to the saving numbers in energy units which are always calculated for a specific case. The presented chart only acts to compare different measures.

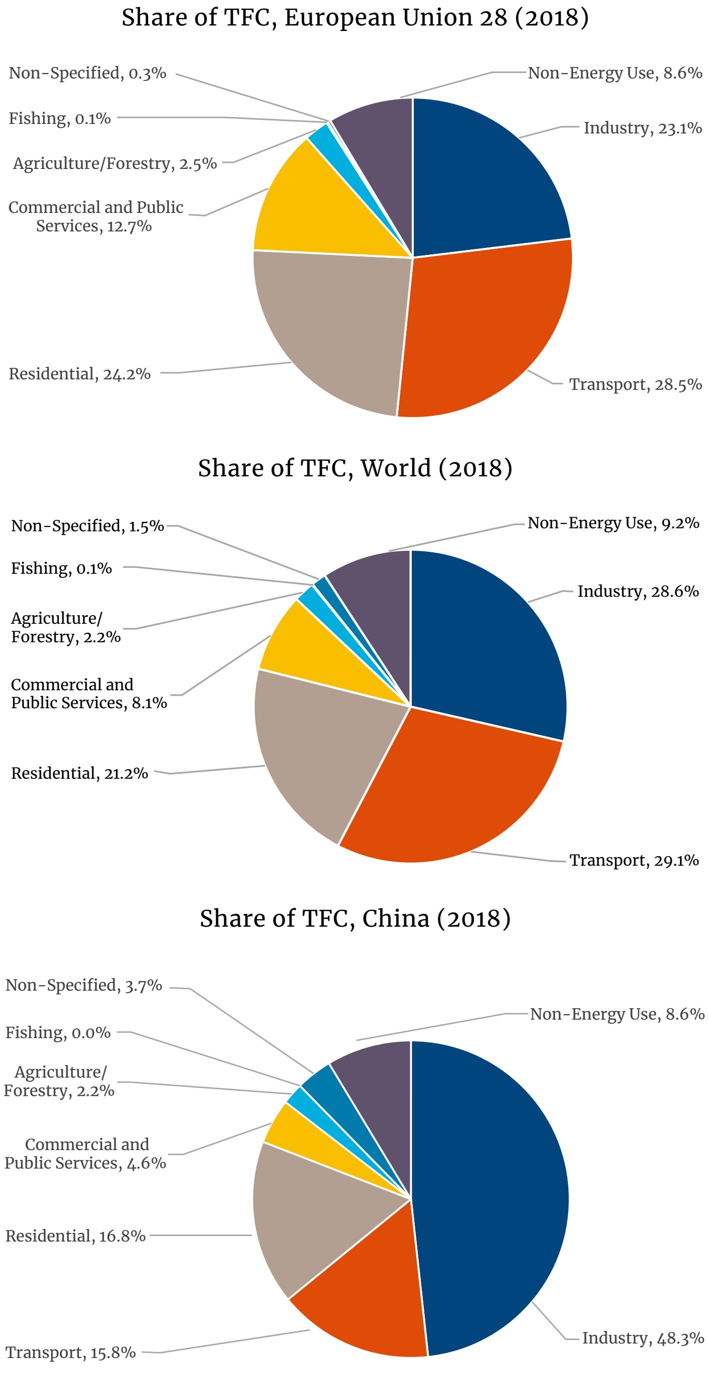


2 Introduction on Energy Efficiency in Industry

2.1 Energy Consumption and Status of Energy Efficiency

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

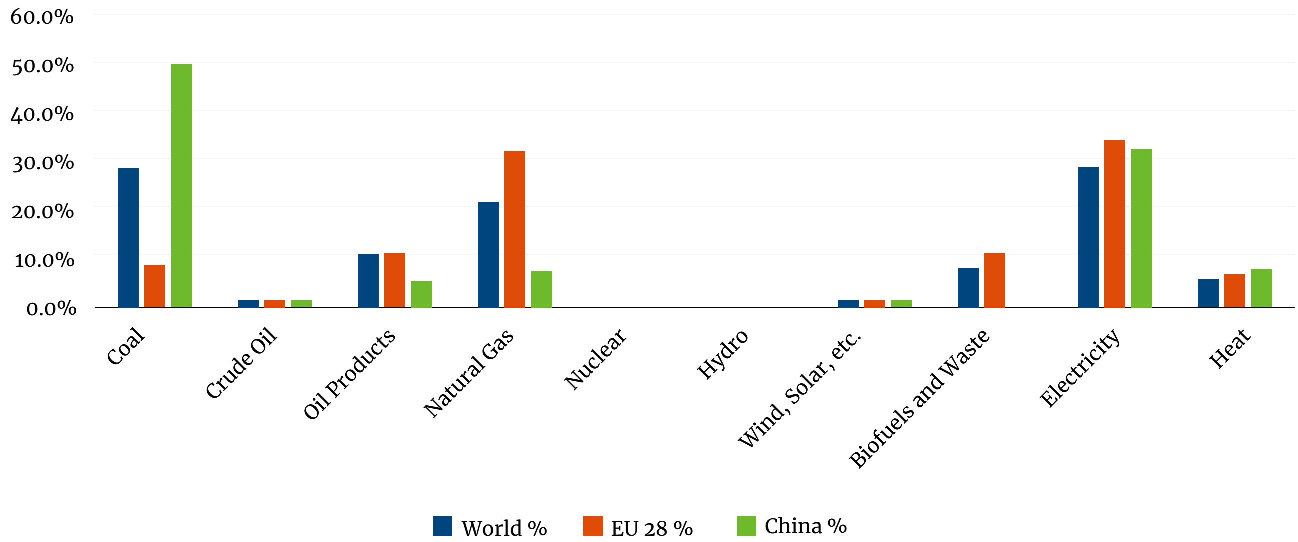
Figure 3: TFC Shares



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 4: TFC Shares/Industry



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

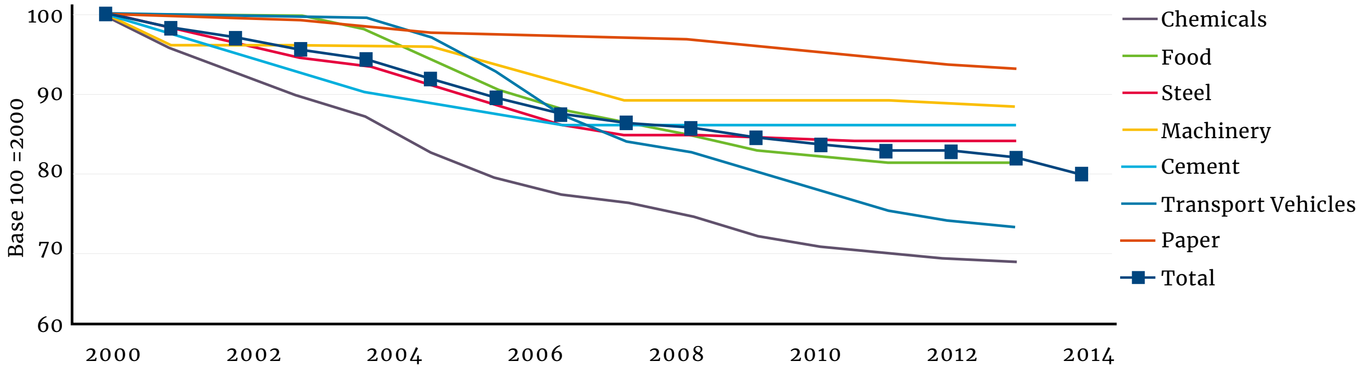
Energy efficiency in industry is considered to be one of the most powerful measures to reduce overall energy consumption and GHG – not only due to the size and importance of the industrial sector, but also because there are relatively few actors in comparison to others sectors. Thus, efficiency changes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

[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.

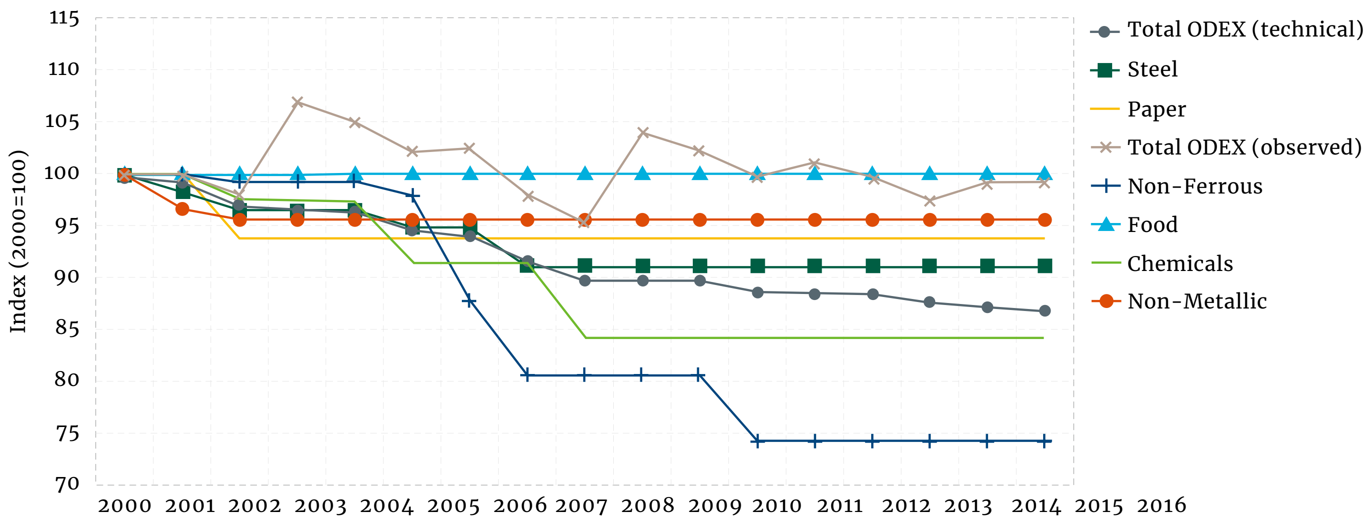
Figure 5: ODEX Indicator- Industrial Sectors European Union



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 6: 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 shows an overall potential summing up to 600-900 Mtoe/year and 1,900–3,200 Mt CO_2 savings per year based on commercial, cost-effective proven technologies. (Fawkes, 2016). These figures correspond to global improvement potentials of around 18 - 26 % of global industrial energy uses and 19 – 32 % of global CO_2 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 as "**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 methods 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 % over the period 2005 to 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 an overall greenhouse gas emission **reduction of 55 % by 2030**. Within this package, energy efficiency was specified as the first key objective because it was considered to be 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**, compared to a 'business as usual' scenario. Additionally, the new target for **renewable energy share** was set to at least **32 %**

[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**.

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.

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 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 limitations, especially due to ongoing practice and cost constraints. The more the "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 (WHR), 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 optimize steam systems** (minimize the number of heat transformations, preheating water or air, using energy efficient heat exchanger designs, minimizing/optimizing simultaneous heating and cooling),
- Optimize **cooling and refrigeration**,
- Recognize the effects of **water chemistry** (mineral salts, dissolved gases etc.) on water quality/treatment requirements,
- Install **combined heat and power** instead of high-temperature heat losses,
- Apply **heat recovery** both within one companyy or also to neighboring heat users or district heating systems,
- Use **waste heat to power** for industrial processes with high waste heat temperatures,
- Convert waste from production as an **energy source** (after screening options for re-use or recycling).

[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 Ceramics Sector

The following chapter provides an introduction to overall production processes in the ceramics sector and their relevance to overall energy consumption as well as a statistical overview of production and energy consumption related figures in Europe.

3.1 Description of the Production Process and Process Steps

The European ceramics sector comprises a wide range of final products, as shown below.

Figure 7: Types of Products – Ceramics Sector

Source: (Cerame-Unie, Cerame-Unie Facts and Figures, 2021)

As the BREF document is currently under review, last production figures for Europe date back to 2009. These figures show the **relative importance of wall and floor tiles** as well as **bricks and roof tiles** in terms of overall production shares and also energy consumption shares.

Table 1: Production and Energy Consumption Figures Ceramics Industry Europe modified from: (EU Merci, 2018), (Ecofys, Fraunhofer Institute for Systems and Innovation Research; Öko-Institut, 2009)

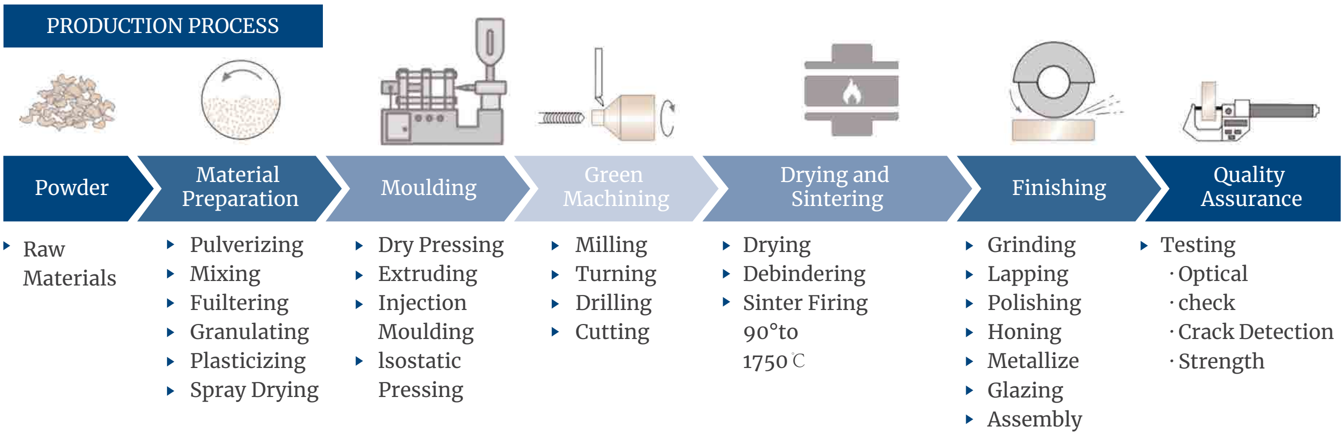
Product	Share of Energy Consumption per Sector	Production (Mt)
Wall and Floor Tiles	42%	25
Bricks and Roof Tiles	38%	55
Table and Ornamental Ware	6%	0.5
Refractory Products	7%	4.5
Sanitary Ware	3%	0.5
Technical Ceramics	2%	0.15
Vitrified Clay Pipes	1%	0.7

The major production stages are similar for all types of ceramics production:

- Raw material preparation
- Moulding and green machining
- Drying
- Sintering (firing) and
- Finishing.

The typical sub-steps are shown in the following chart:

Figure 8: Ceramics Production Steps



Source: adapted from (Vogt Ceramic, 2021)

Differences in the production processes for the different types of ceramics relate to factors like:

- The raw materials used,
- The shaping process,
- The firing temperatures employed.

and depend on the specific needs for the particular products (shape, dimensions and required properties etc.).

In the following, the main production stages relevant for all types of ceramic products are explained.

Raw Material Preparation and Forming[7]

Preparation of raw materials involves putting the ceramic mixes together with the required additives for the following stages of the process. The reduction of their particle size is usually achieved by dry or wet grinding.

The so-called "green body" is the term for the object formed before firing. There are different types of preparation and shaping, depending on the final product.

- **Dry-pressing** (pressing of powder into pressing dies) – applied for tiles.
- **Spray drying** (producing dry powder from a liquid or slurry by rapidly drying with a hot gas, leads to highly uniform granules).
- **Extrusion** (flow of a wetted, plastic mass through a die under pressure) – applied for bricks and roof tiles.
- **Slip casting** (preparation of a slurry of the raw powders, which is then cast into plaster molds, through which the water is slowly absorbed. This leaves the object as a crust inside the mold) - applied for all sanitary ware. (Agrafiotis & Tsoutsos, 2001)
- **Fusion casting** (The material is pre-melted and poured into moulds. This type of forming requires controlled cooling and solidification to avoid fractions, is highly energy intensive and used for specialized ceramics. (EU Merci, 2018)

[7] Including processes material preparation, moulding, green machining from above chart

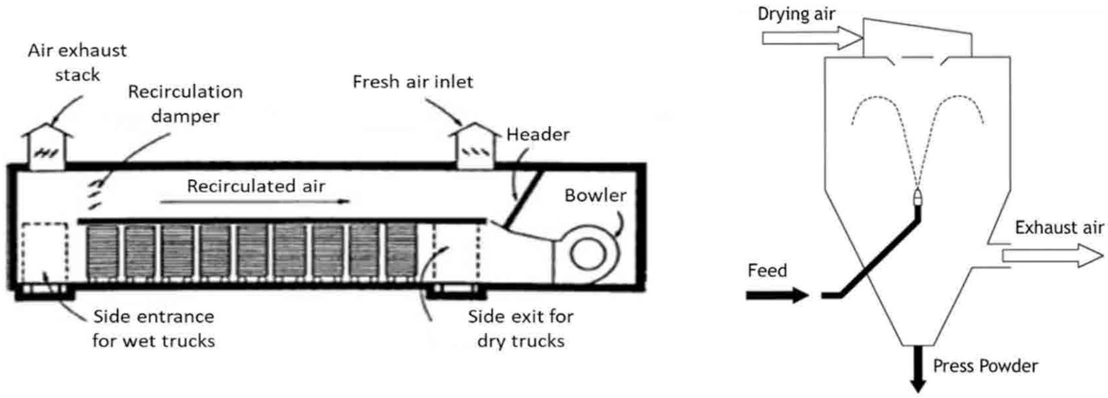
Drying and Firing[8]

For products which are not dry-pressed, the next step is drying, i.e., the slow expulsion of water before the firing process. Typical temperatures vary from 60 to 200° C. Drying times depend on the initial moisture content and on the dimensions of the ware: Sanitaryware requires the most time and tiles the least.

Apart from the ceramic product, the molds used for slip-casting are also dried before re-use. (Agrafiotis & Tsoutsos, 2001)

Schemes of tunnel dryers and spray driers are given below.

Figure 9: Scheme of a Tunnel Dryer (left), Spray Dryer (right) (Oliveira, Iten, Cruz, & Monteiro, 2020)



Firing is at the core of ceramics production. The products are heated up in a kiln at temparatures **ranging from 800°C-1800°C**. Depending on the products and types of kilns, the process takes up to several days. (Szczeniak, Bauer, & Kober, 2020). Firing for some products (tiles, sanitaryware and the cheapest tableware) requires only one stage. For other products, a **series of firings** might be required. The first firing is used for increasing the strength of the ceramic substrate (called biscuit). In the tableware sector, decoration is applied before applying the glaze, and a second firing called the glost firing follows. Another type of decoration can be fixed by the enamel firing.

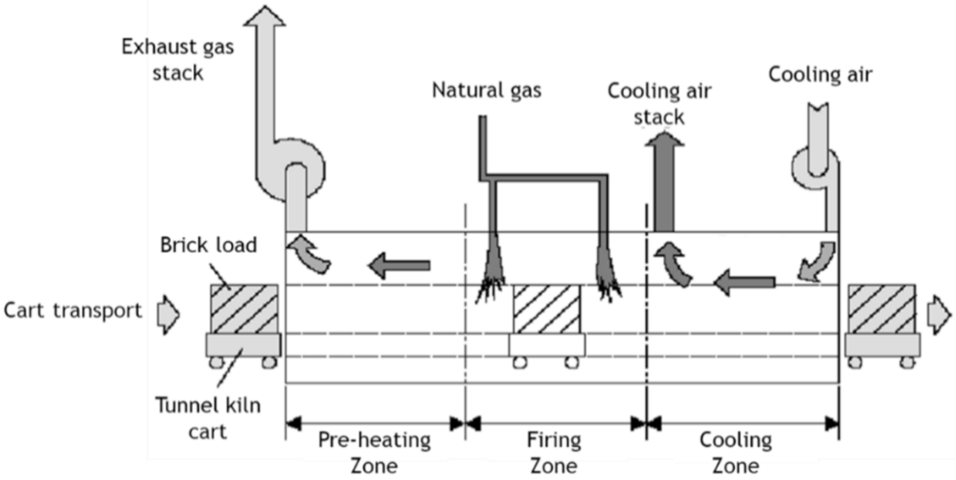
In principle, there are **continuous or intermittent (batch) kilns**, which can be further classified as:

- Tunnel kilns (products are transported in kiln cars; these are normally open at the beginning and end; heating occurs at the centre),
- Rotary kilns,
- Roller kilns (using refractory roller conveyors for the transportation of products),
- Intermittent/discontinuous kilns (Oliveira, Iten, Cruz, & Monteiro, 2020).

Diagrams of the tunnel kilns and roller kilns are shown below.

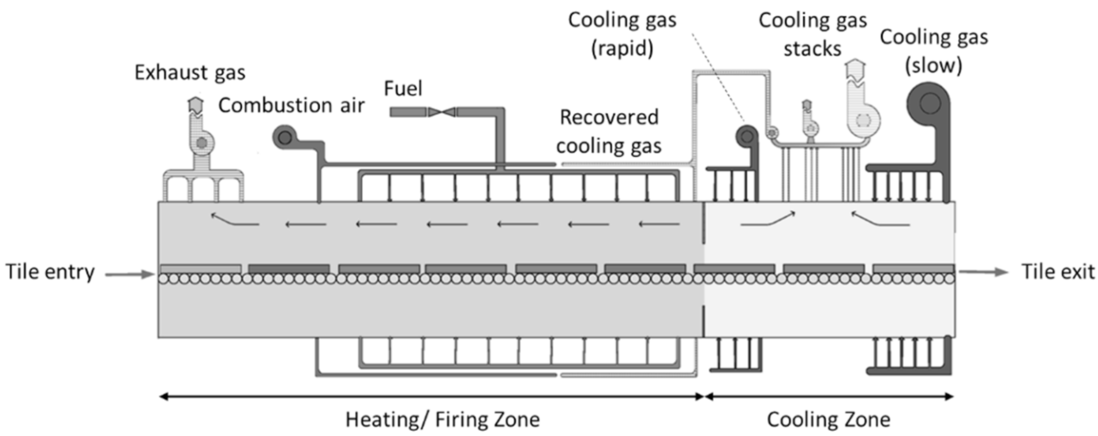
[8] In the above chart: drying and sintering

Figure 10: Scheme of Tunnel Kiln



Source: (Oliveira, Iten, Cruz, & Monteiro, 2020)

Figure 11: Scheme of a Roller Kiln



Source: (Oliveira, Iten, Cruz, & Monteiro, 2020)

Different types of energy are used for heating purposes: fuel oil, diesel fuel, LPG (liquid petroleum gas), methane or natural gas, coal (coke) and electricity. (Agrafiotis & Tsoutsos, 2001) In Europe, the main fuel is gas; technical ceramics also use electricity kilns. (Kollenberg, 2013).

Heat energy from fuel is needed for drying and firing, while electrical energy is required for grinding operations in the preparation of raw materials, pressing operations during shaping, as well as in automation and in handling and moving the pieces during processing. (Agrafiotis & Tsoutsos, 2001)

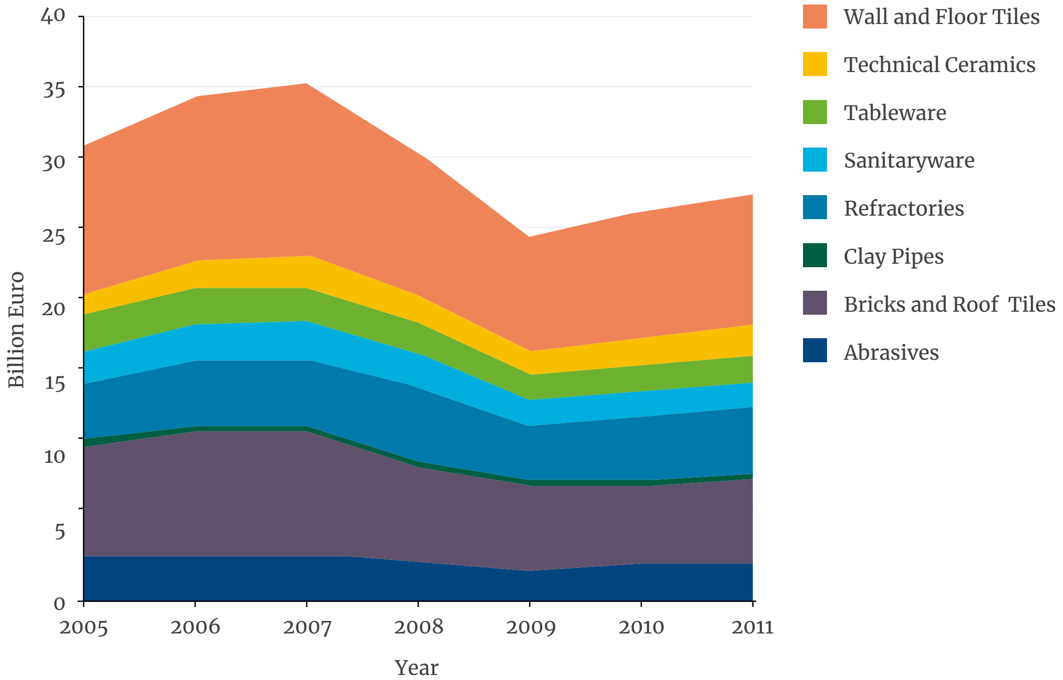
3.2 Current Situation and Development of Energy Efficiency in the Sector

This chapter further explains the current situation of energy consumption and energy efficiency of the ceramics sector in Europe and provides an overview of the major energy-consuming processes relevant for this sector.

3.2.1 Energy Statistics and Benchmarks Ceramics Sector

Below chart provides an overview of ceramics production in European countries, which adds up to production output of approximately 87 Mt/year (see Table 1 in the previous chapter) or 28 billion EURO (see Figure 12 below), respectively. The largest four production countries (Italy, Germany, Spain, France) covered more than 60% of overall production value in 2011.[9]

Figure 12: Ceramics Production Values in Europe

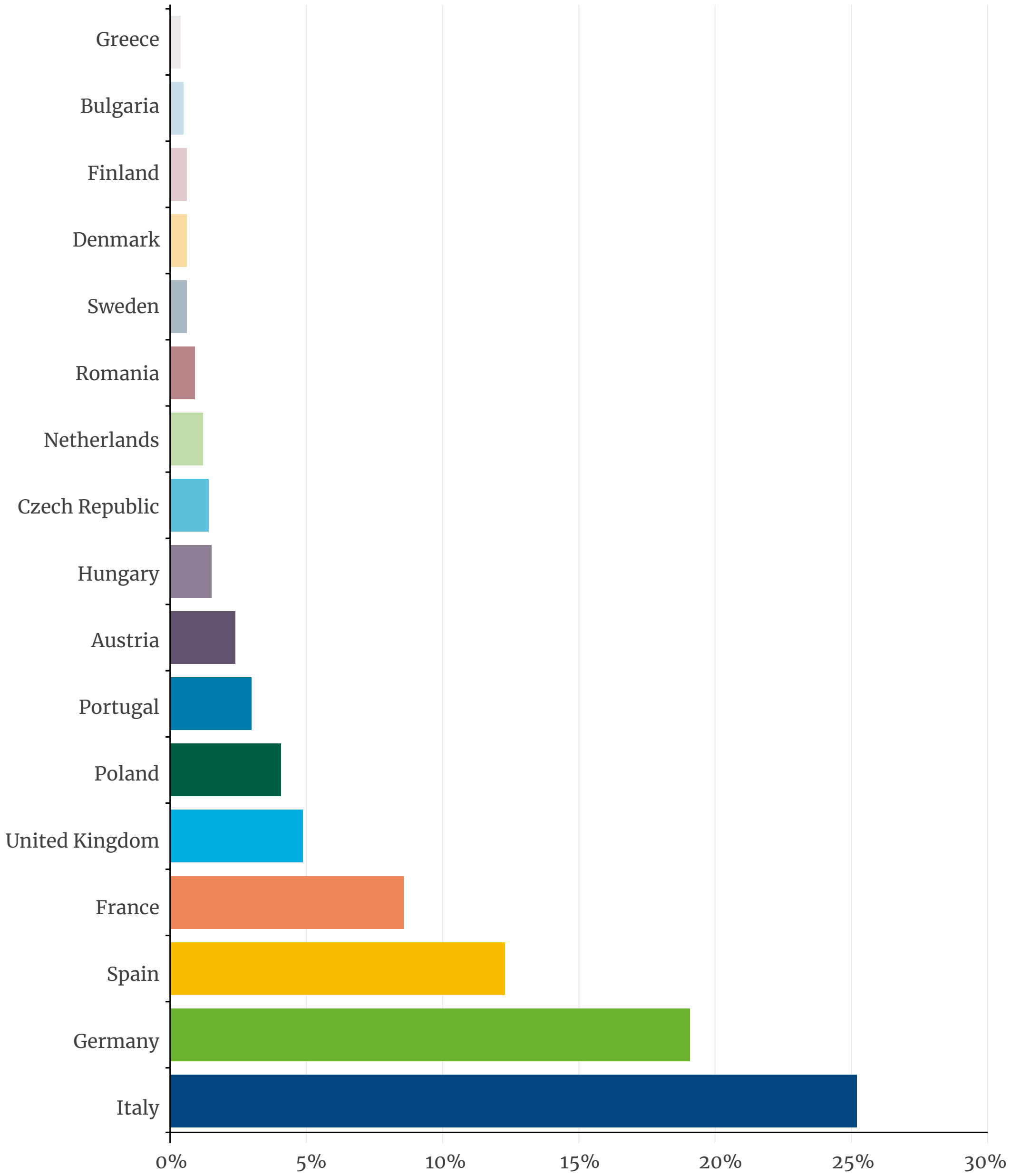


Source: (CeramUnie, 2012)

[9] Detailed updated production values in tonnes of product are currently not available; the BREF document is currently under review and will be updated until 2025. The Ceramic Union only presents data in monetary terms; Odyssee Data (database available for other sectors) could not be identified for this sector.

The following chart shows the percentage of production value (in monetary terms) in European countries.

Figure 13: Ceramics Production Value Shares in Europe



Source: (CeramUnie, 2012)

Unit energy consumption is defined as the energy input necessary for the production of one unit of output. In the case of ceramics production, this figure relates to "one tonne ceramics produced". However, such average figures only have limited value, as the types of products and respective energy consumption vary considerably. Therefore, in the following table, the unit energy consumption is indicated for specific product types.

The European Ceramic Union states that the energy consumption for production of bricks, wall and floor tiles decreased considerably during the 1990s and 2000s – by 47% and 39%, respectively. However, the reference unit for these figures is the energy required for producing "1 m^2 brick wall". This means that energy efficient production is not solely responsible for this development, but also changes in product design leading to less material needed for constructing a 1m^2 brick wall (e. g. light weight bricks).

Table 2: Unit Energy Consumption and Share of Energy Consumption per Sub-Sector – adapted from: (EU Merci, 2018)

Product	GJ/t	MWh/t	Share of Energy Consumption per Sector	Production (Mt)
Wall and Floor Tiles	5.6	1.6	42%	25
Bricks and Roof Tiles	2.32	0.6	38%	55
Table and Ornamental Ware	45.18	12.6	6%	0.5
Refractory Products	5.57	1.5	7%	4.5
Sanitary Ware	21.87	6.1	3%	0.5
Technical Ceramics	50.39	14.0	2%	0.15
Vitrified Clay Pipes	5.23	1.5	1%	0.7

Comparing unit consumption values, the product types with the **highest energy consumption requirements are table and ornamental ware** as well as **technical ceramics. These products reach unit energy consumption values higher than 12 and 14 MWh per tonne of product**, respectively. On the lower end of energy consumption per tonne of product are **bricks and roof tiles** with less than **1 MWh/tonne** of product. Thus, one of the most important conclusions is that comparing different ceramic sub-sectors' "average" energy consumption is only of limited value due to different production portfolios.

Each attempt to reduce overall (final) energy consumption ultimately also targets the broader goal of **greenhouse gas emission reduction**. This can be achieved via various ways, including efficiency measures reducing final energy consumption, fuel switch and further initiatives (see chapter 4.11), but also through production design changes that lead to lower unit energy consumption (see chapter 4.2).

Table 3 shows current levels of some product benchmarks in the EU ETS (European Commission, 2021), which are defined in tonnes CO_2 per tonne of product. Additionally, the table presents the average value of the 10 % most efficient installations. By comparing the most efficient installations and benchmark values, it can be seen that there is further room for reducing CO_2 emissions, although this is limited.

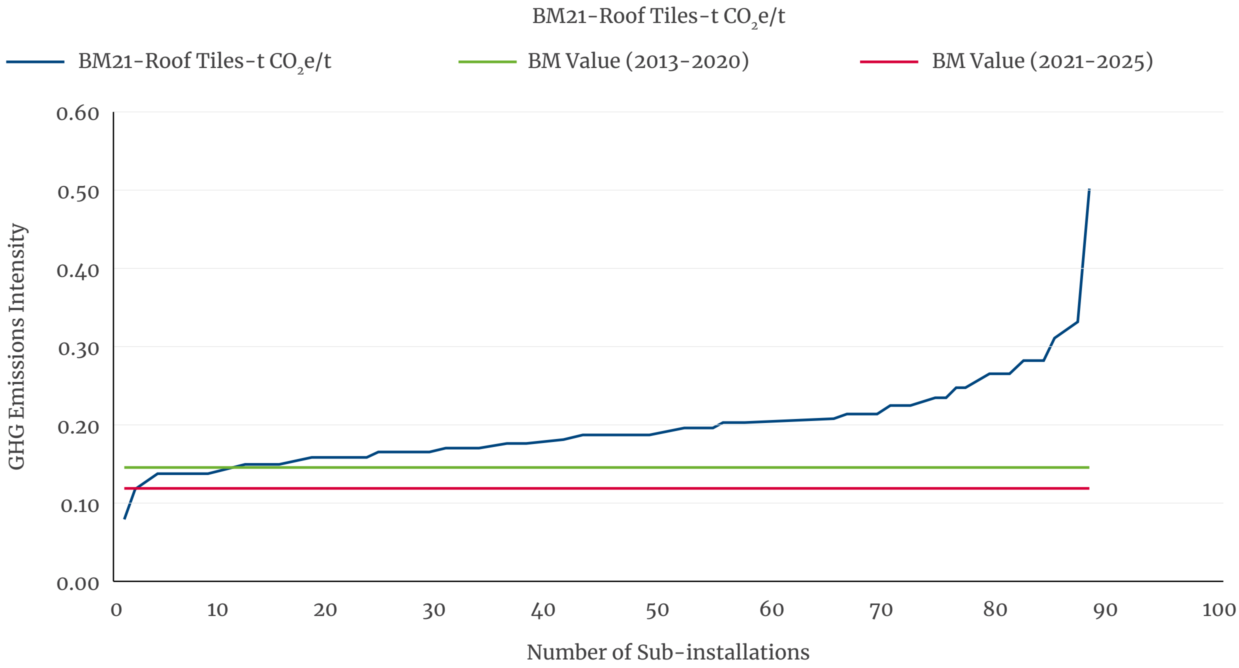
Table 3: Product Benchmarks

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
Facing Bricks	0.094	0.106
Pavers	0.140	0.146
Roof Tiles	0.130	0.120

Source: (European Commission, 2021)

Over the course of benchmark definition, the European Commission also collected production data and compared actual CO_2 emissions. For the case of roof tiles, the following evaluation is presented:

Figure 14: Statistical Data on GHG Emission Intensity of Roof Tiles in Europe



Source: (European Commission, 2021)

The blue line shows the actual GHG emission intensity of European roof tile producers, while the red line shows the Benchmark (BM) value for the current EU ETS phase 2021-2025. Average GHG emissions intensity of all installations in 2016/2017 amount to 0.197 t CO_2e/t, while weighted average GHG emissions intensity of all installations was 0.185 t CO_2e/t[10]. The ten most efficient installations averaged 0.13 t CO_2e/t. This means that the "average" producers still have room for improvement (or the need to buy emission certificates).

Another fact worth mentioning in the context of GHG is the share of **process emissions**. Depending on the specific minerals and local geology, around 16% of overall CO_2 emissions[11] are process-emissions. These are emissions, which are not related to fuel-input, but inherent to the breakdown of carbonates in the raw materials such as limestone, dolomite or magnesite. These emissions are a natural by-product of the firing process and cannot be avoided (without changing the inputs). As pointed out in the Ceramic Sector's Roadmap for achieving 2050 GHG reductions, cogeneration and the use of alternative fuels including biogas or syngas should be considered in addition to improvements in fuel emissions, including heat recovery and electrification of kilns, which only lead to improvements when low-carbon electricity sources are used. (CeramUnie, 2012)

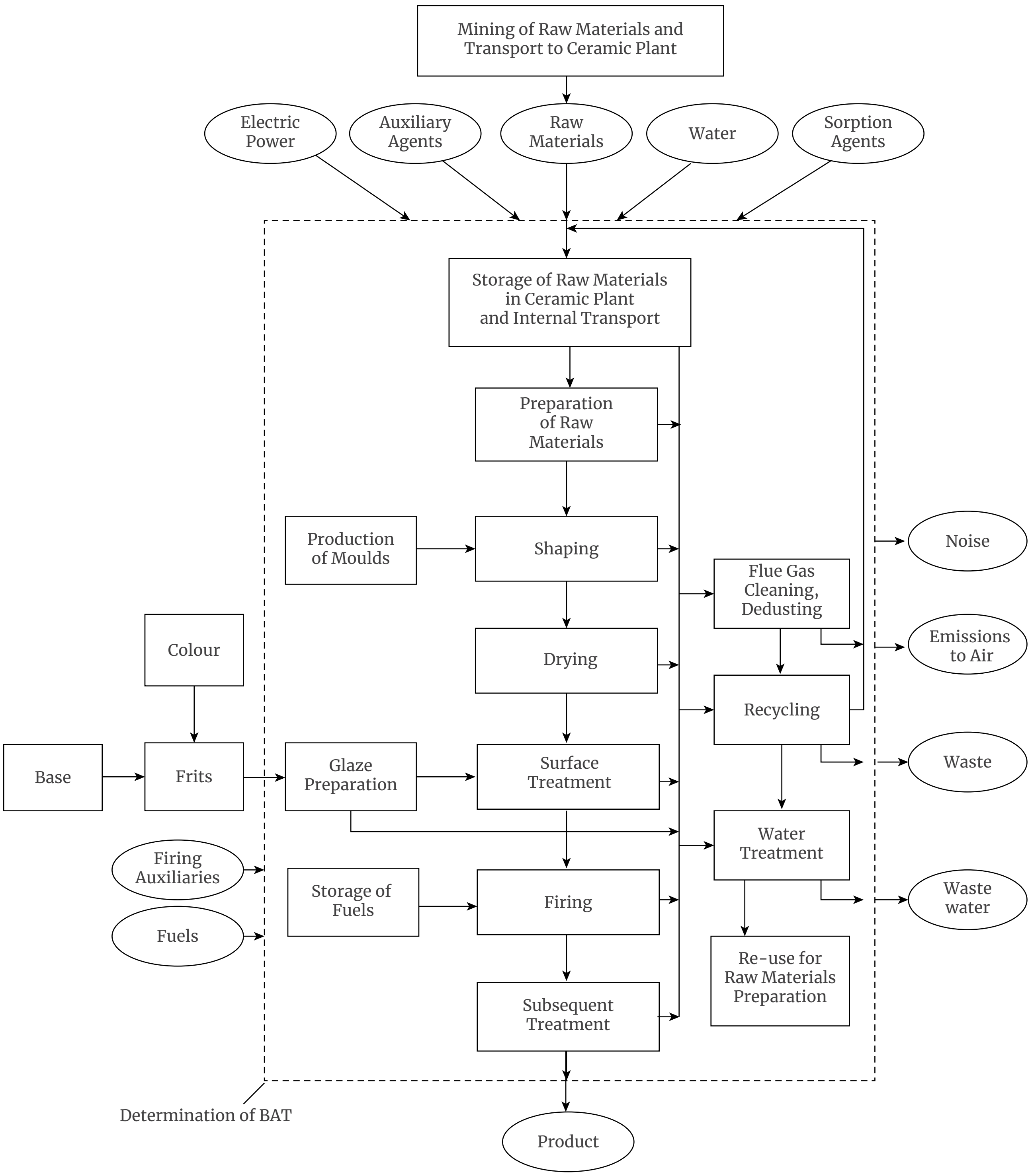
[10] The weighted average is calculated for each benchmark by dividing the sum of the attributed emissions (CO2) in 2016 and 2017 by the sum of activity levels (i.e. production volumes) in 2016 and 2017

[11] Figures for the bricks and roof tiles, refractories and wall and floor tiles sub-sectors

3.2.2 Energy and Material Flows

The following chart provides an overview of the major energy and material flows:

Figure 15: Energy and Material Flows Ceramics



Source: (European Commission, 2007)

3.2.3 Energy Intensive Processes

To determine specific energy saving potentials and measures, one of the first steps is to identify major energy consuming processes.

The significant differences in ceramic sub-sectors mentioned in the previous chapter mean that all international comparisons and single figures have to be interpreted with caution. Nevertheless, the figures below can be taken as a rough indication of unit energy consumption. They also underline the **dominance of thermal process requirements over electricity consumption** with shares in the range of **83-91% of overall energy consumption**[12].

Table 4: Unit Energy Consumption and Share of Energy Consumption per Sub-Sector – own chart, data from: (SIDBI, 2019)

Country	Unit Electricity Consumption	Unit Thermal Energy Consumption	
	kWh/t	kWh/t	GJ/t
India	210	1557.4	5.6
China	256	1220.3	4.4
Italy	139	1348.2	4.9

As shown in Figure 16, the major energy consumption share can be attributed to the kiln. Specific shares vary depending on the type of product and the specific production steps (see previous chapter).

Heat energy from fuel (mainly gas) is required for drying and firing, whereas electrical energy for grinding/raw material preparation, pressing/shaping and for handling/moving the components. (Agrafiotis & Tsoutsos, 2001)

Typical energy consumption figures for the main energy consuming sub-processes for the example of **tiles production** are given below:

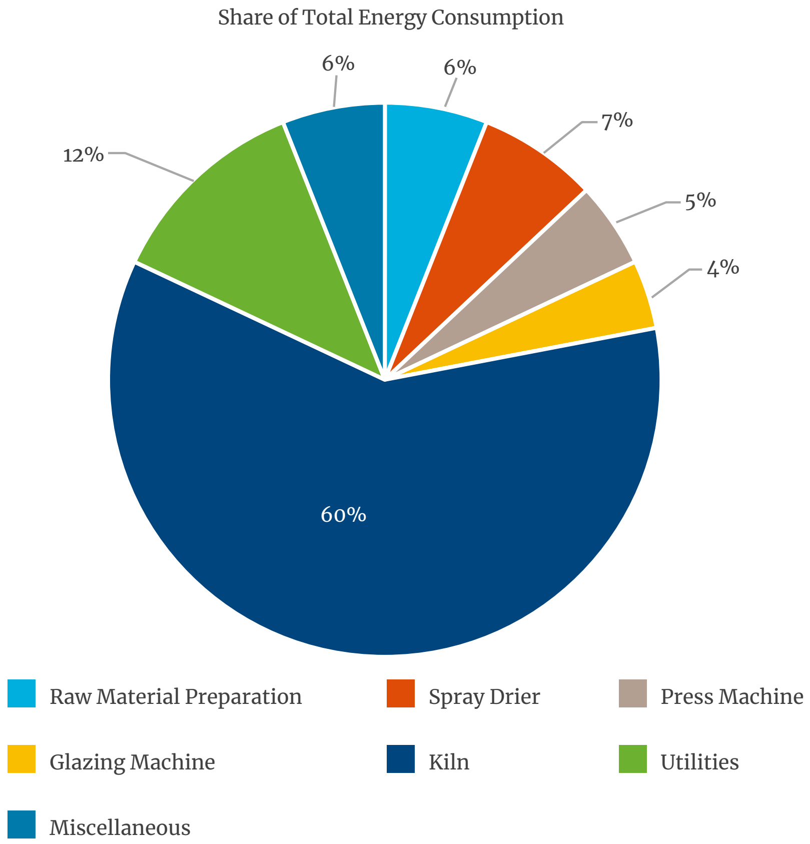
Table 5: Energy Consumption of Sub-Processes for Ceramic Tile Manufacturing, adapted from: (UNIDO, 2016)

Production Process	Type of Energy	Unit	Benchmark min	Benchmark max	Benchmark Average	Benchmark Average [kWh]
Spray Drying Process	Thermal	GJ/ton	0.98	2.2	1.59	442
Drying Process	Thermal	GJ/ton	0.25	0.75	0.5	139
Firing	Thermal	GJ/ton	1.9	7.3	4.6	1278
Pressing	Electric	GJ/ton	0.05	0.15	0.1	28

Overall shares of energy consumption for the average ceramic are provided in source from India (SIDBI, 2019). Although all average figures have to be treated with caution, these shares can serve as a rough estimation relevant for most types of ceramic production. In any case, the kiln remains, by far the largest energy consumer and thus also the starting point for all optimisation efforts.

[12] For better comparability of data, thermal energy figures are shown in kWh and GJ.

Figure 16: Relevance of Process Steps for Energy Consumption



Source: (SIDBI, 2019)

Major points affecting specific energy consumption according to the BAT document comprise:

- Improved design of kilns and dryers,
- Recovery of excess heat from kilns,
- Cogeneration/combined heat and power plants,
- Substitution of heavy fuel oil and solid fuels by low emission fuels,
- Modification of ceramic bodies (European Commission, 2007).

The next section presents specific measures which also include the above points.

4 Sector Specific Energy Efficiency Measures

Table 6 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 reduction.

Table 6: Ceramic Sector Energy Efficiency Measures

Chapter	Measure	Process
4.1	Use of Dry Route for Raw Material Preparation	Raw Material Preparation
4.2	Improvements in Ceramic Design	General Process
4.3	Airless Drying	Drying
4.4	Controlled Dehumidification	Drying
4.5	Exhaust Air Recirculation in Spray Dryers	Drying
4.6	Drying Air Preheating	Drying
4.7	High-efficiency Burners	Firing
4.8	Low Thermal Mass Kiln Cars and Furniture	Firing
4.9	Electric Kiln and Drying	Drying/Firing
4.10	Microwave Assisted Firing and Drying	Drying/Firing

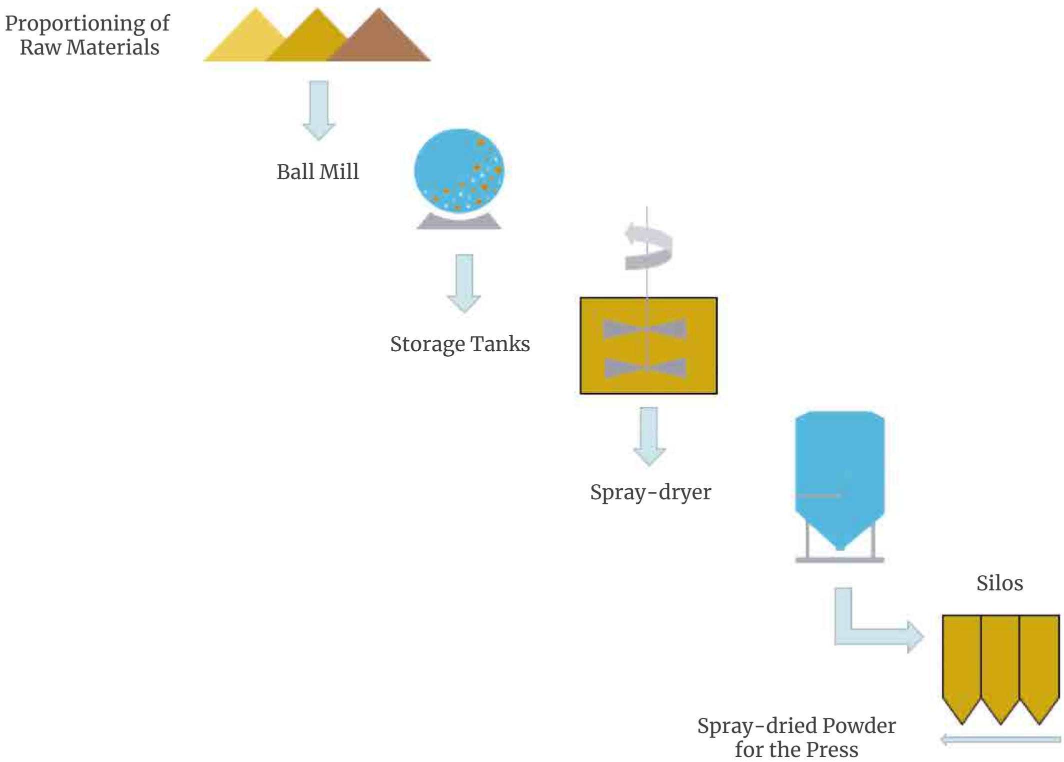
4.1 Use of Dry Route for Raw Material Preparation

4.1.1 Description of Baseline Situation and Energy Consumption

It is important to reduce the raw material's particle size in order to improve material blending, increase the materials surface area, liberate impurities or to modify the shape of the particles. After crushing, which reduces large lumps from cm size to 1-2mm, further particle reduction is achieved by grinding. Traditionally, this is realised under wet conditions, using wet grinding and spray drying for ceramic tile manufacturing. (Kocak & Karasu, 2018)

The following diagram shows the typical process steps under wet conditions.

Figure 17: Raw Materials Preparation – Wet Route



Source: (Mezquita, Monfort, & Salvador Ferrer, 2017)

Dry, finely ground powders are mixed with water (appr. 65-72 % solids by weight) to form a slurry, "which is then atomized inside the drying chamber by either a slotted, spinning centrifugal disc or a spraying nozzle" (Kocak & Karasu, 2018).

Burned gases evaporate in the process, leaving 4–6 % of water and a hollow, spherical agglomerate. In the spray dryer, the material is moved due to the vibration and streaming air and can deliver different granulate structures, depending on the selection of nozzle orifice diameter, feed pressurization and slip viscosity.

The below table shows the typical consumption figures of the wet route. The table shows all values per one Mg (Mega-gram), which is identical to tonnes of dry substance.

Table 7: Key Consumption Figures for Wet Route

Water, energy consumptions and CO_2 emissions in the raw preparation by the wet method. (a) d.s.: dried solid (b) HHV: Higher Heating Value (c) Emission factor for natural gas: 0.202 kg CO_2/kWh (IPCC,2006).

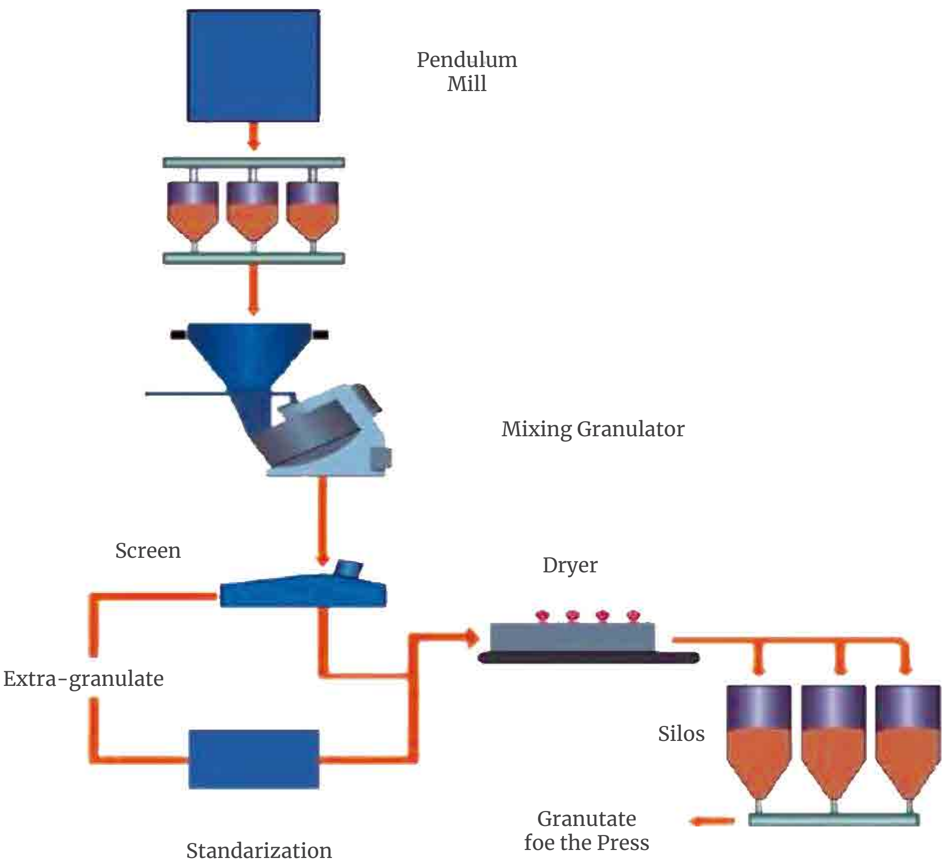
Wet Process	Consumption
Water Consumption	0.47-0.59 m^3/Mg d.s.[a]
Electrical Energy Consumption	50-54 kWh/Mg d.s.
Thermal Energy Consumption (in HHV[b])	442-462 kWh/Mg d.s.
CO_2 Direct Emissions[c]	80-84 kg CO_2/Mg d.s.

Source: (Mezquita, Monfort, & Salvador Ferrer, 2017)

4.1.2 Suggested Measures of Improvement

As an alternative to the wet route, it is suggested to use the dry route, which consists of a pendulum mill and subsequent granulation (Mezquita, Monfort, & Salvador Ferrer, 2017), shown in the below diagram.

Figure 18: Raw Materials Preparation – Dry Route



Source: (Mezquita, Monfort, & Salvador Ferrer, 2017)

[13] Too fine particles are added to the next batch, to big participles can be ground and returned to the fluid bed dryer or added directly to the press powder.
[14] Mg= tonne

Here, in comparison to spray drying – which delivers almost all products at appropriate size and moisture content – the pelletized body at initial stages is partly too big or too small and has to be reprocessed. The resulting granules have the same levels of water absorption (3%) as the spray-dried version and the same drying and firing cycles. The tile surface is "extremely uniform and ideal for matt and gloss applications".[13] In terms of energy efficiency and also water efficiency, the dry route shows considerable advantages, as depicted in the below table[14].

Table 8: Key Consumption Figures for Dry Route

Water, energy consumptions and CO_2 emissions in the raw preparation by the wet method. (a) d.s.: dried solid (b) HHV: Higher Heating Value (c) Emission factor for natural gas: 0.202 kg CO_2/kWh (IPCC,2006).

Dry Process	Consumption
Water Consumption	0.12-0.16 m^3/Mg d.s.[a]
Electrical Energy Consumption	31-35 kWh/Mg d.s.
Thermal Energy Consumption (in HHV[b])	88-108 kWh/Mg d.s.
CO_2 Direct Emissions[c]	16-20 kg CO_2/Mg d.s.

Source: (Mezquita, Monfort, & Salvador Ferrer, 2017)

4.1.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Considering the key figures given for the wet (Table 7) and dry route (Table 8), respectively, thermal savings in the range of 78% or 354 kWh per tonne of product are derived. Electricity savings add up to 37% or 19 kWh per tonne of product.

Table 9: Key Facts of Measure – Use of Dry Route for Raw Material Preparation

Key Facts of Measure – Use of Dry Route for Raw Material Preparation	
Investment Cost:	Maintenance cost savings 2.5€/tonne and personnel (2 instead of 3 people) (Kocak & Karasu, 2018)
Energy Savings: (thermal and electricity)	1274 MJ/$t_{ceramics}$ (354 kWh/t) decrease of thermal energy demand 19 kWh/ $t_{ceramics}$ decrease of electrical energy demand
CO_2 Mitigation:	83 kg CO_2/$t_{ceramics}$
Advantage:	• No need for drying power • Less media and lining war than wet milling • Less shrinkage • Start/Stop at any time
Disadvantage:	• More dust compared to wet route • Wet route offers narrower particle size and better homogenisation

4.2 Improvements in Ceramic Design

4.2.1 Description of Baseline Situation and Energy Consumption

Several factors, which go beyond the simple optimisation of process steps, affect the (unit) energy consumption of ceramic production. One of the important factors are the raw materials and additives used - their characteristics impact the required mass for delivering the desired product and firing characteristics and thus energy consumption. Additionally, the types of forms and slips used play a major role.

Measures which reduce rejects in all process steps such as fracture after firing, wear in the forming process and grinding waste will considerably reduce energy consumption in general. In contrast to glass or metal, ceramic components can only be re-used to a very limited extent, since the sintering process causes the raw materials to change irreversibly. Though it is possible to grind up broken pieces and material and to add them to raw material, the extent to which it can be done is unsubstantial. The most "expensive" waste (both in terms of money and energy) is grinding waste from hard machine; this material already underwent several energy intensive process steps. (Kollenberg, 2013)

The baseline situation for this measure is thus the current – non-optimized – product design, which varies for different sub-sectors as well as for single mills.

4.2.2 Suggested Measures of Improvement

Suggested measures of improvement address the optimization of the product design including materials used. Typical interventions include:

- New materials and design that require less raw material (for the same purpose) and shorter firing durations,
- New material compositions including pore-forming agents (e. g. carbon nanotubes),
- Incorporating residues to produce thermal energy,
- Using additives (such as incineration ashes, waste glass, low sintering clays) to reduce the sintering temperatures,
- Identifying new/lighter ceramic materials with identical mechanical properties. (Oliveira, Iten, Cruz, & Monteiro, 2020).

Specific potential improvements are provided in the following table, which summarizes findings from a comprehensive R&D project designed for developing energy saving concepts for the European ceramic industry.

Table 10: Examples of Material/Design Related Improvements

Sub-Sector	Material/Forming	Additives	Other
Masonry Bricks, Roof Tiles	Use better quality clay to reduce water requirement	Sintering additives: ashes, waste glasses, glass and mineral wools, low sintering clays leading to lower sintering temperature	Waste graphite, petroleum coke, coal-clay as fuel additive
Pavement and Facing Bricks	Same as for masonry bricks; designs of bricks with less mass	Same as for masonry bricks	Same as for masonry bricks
Table Ware	• New materials like Li-containing feldspars or colemanite[15] resulting in reducing the sintering temperature by up to 200°C • Special bodies and glazes with allow single-firing (instead of double-firing)	--	The more colours possible within one firing step the less energy needed
Sanitary Ware	• New materials like Li-containing feldspars or colemanite resulting in reducing the sintering temperature by up to 200°C • Optimized bodies from traditional clays and china clays leads to decrease in the firing temperature up to 50°C	--	Optimize grain size distribution of feldspar/ other additives leads to improved reactivity, less energy

Source: based on (Kollenberg, 2013)

One typical example of changed design are so-called *Poroton-bricks*. These are hollow bricks, which are perforated so that they are not only lighter, but also have better thermal conductivity. Additionally, such bricks can have an additional filling, in this case with isolating material.

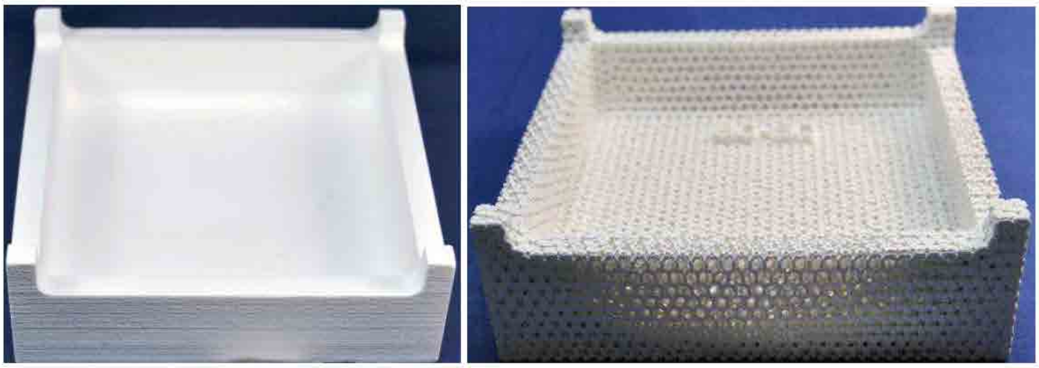
Figure 19: Poroton Bricks

Source: (Wienerberger, 2021)

Current developments also apply bionic approaches – this means that at points where the component is not exposed to high material stress, the material is reduced to its minimum, as it is the case with a bone. Design is often realized with 3D printing. An example is shown in the picture below – conventional and optimized sinter bowls.

[15] Mixture of Feldspars from K and Na

Figure 20: Sinter Bowls – Conventional (left) and Optimized (right)



Source: (Kollenberg, 2013)

4.2.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

It is not possible to come up with a uniform energy saving potential for different types of actions, improvements and design changes. However, as an example, it is pointed at how a 15 % increase in material porosity can lead to increased water absorption and decreasing compressive strength and thus considerable energy savings in the drying phase. (Oliveira, Iten, Cruz, & Monteiro, 2020).

Potential energy savings relate to the firing phase (firing temperature reduction), drying phase (better water absorption) or to less reject (same service with less material).

Table 11: Key Facts of Measure – Improvements at Ceramic Design

Key Facts of Measure – Improvements in Ceramic Design	
Investment Cost:	n.a. (depending on specific intervention), e.g., savings due to reduced temperature by 200°C lead to specific energy consumption reduced by appr. 15% (670 kWh/t for sanitary ware, 135 kg CO_2/t)
Energy Savings: (thermal and electricity)	
CO_2 Mitigation:	
Advantage:	• Energy saving due to reduced firing temperature l • Higher material porosity, more water absorption • Change in design/form – lower material costs with comparable product characteristics
Disadvantage:	• -

4.3 Airless Drying

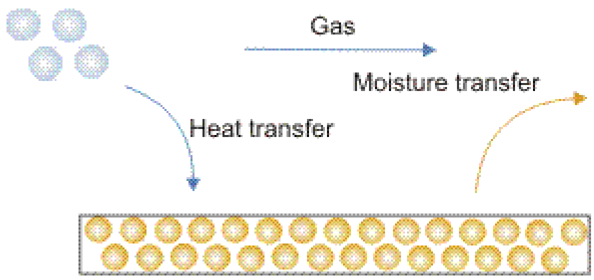
4.3.1 Description of Baseline Situation and Energy Consumption

Drying is a process which reduces the moisture content in a solid through energy influx. The transport of moisture from the interior to the surface of the material can occur in the form of liquid and/or steam. This depends on the type of product and the moisture level. Hot air provides the necessary thermal energy input to evaporate the water from the moist good (Mota Neto, 2008) (Silva & Farias, 2013).

The moist material is heated by means of convection, radiation, conduction, or by internal generation, leading to the evaporation of water. Hot air then absorbs the water vapor (Keey, 1992). This drying process is sketched in Figure 21.

Typically, the thermal efficiency of convective drying is less than 60% (Vasić & Radojević1, 2015). The remaining energy is lost via heat absorption of the product transport equipment (such as kiln cars) and hot air leaks or cold air inlets.

Figure 21: Convective Drying Process



Source (Keey, 1992)

The drying process in the ceramic sector is carried out by using a hot air stream as carrier gas with temperatures between 60 and 200°C. The drying process requires up to 30% of the total fuel consumption (UNIDO, 2016). A scheme of the drying process has already been presented in Figure 9 on page 19.

4.3.2 Suggested Measures of Improvement

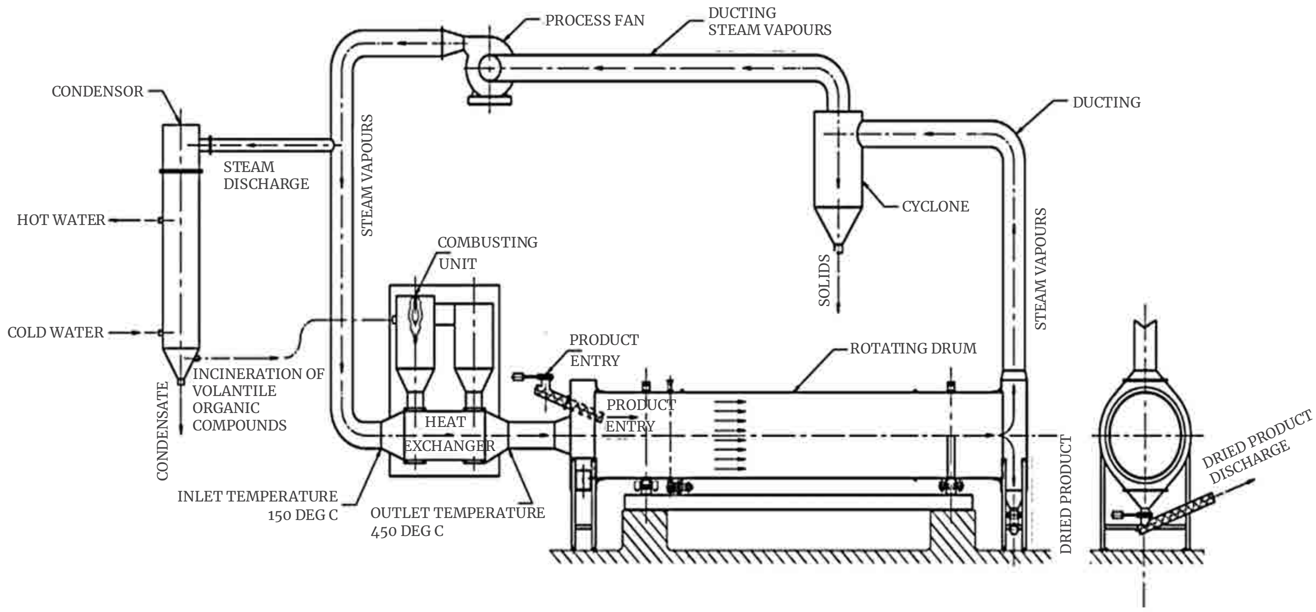
While in a conventional dryer, the exhaust air including the contained thermal energy is released into the environment, in the airless method, a steam cycle is used (Miguel Castro Oliveira, 2020).

The concept of airless drying utilizes superheated steam as the drying medium. The major benefit of airless drying is that superheated steam has heat transfer properties superior to air at higher temperatures. Removing oxygen from the drying process also creates unique environmental and operational benefits (Keith, 2016).

The drying loop is shown in Figure 22.

The operating temperatures are above 250°C, whilst maintaining atmospheric pressure throughout a self-contained, sealed, airless system. This closed loop environment creates energy savings by utilizing the energy in the excess steam (the latent heat). Due to the temperatures of the supercritical steam cycle, all of the moisture is converted into the steam phase and can be removed from the material during the drying process. (Keith, 2016).

Figure 22:Schematic Airless Drying



Source: (Keith, 2016)

4.3.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

This measure can generate savings between 20 and 50% of the thermal energy relating to the drying process (Miguel Castro Oliveira, 2020). A reduction of 35% of thermal energy consumption is realistic.

Table 12: Key Facts of Measure – Airless Drying

Key Facts of Measure – Airless drying[16]	
Investment Cost:	n.a., depends on specific intervention
Energy Savings: (thermal and electricity)	557 MJ/$t_{ceramics}$ (155 kWh/t) decrease of thermal energy demand
CO_2 Mitigation:	31 kg CO_2/$t_{ceramics}$
Advantage:	• Environmental and operational benefits • Better regulation of drying process
Disadvantage:	• More complicated process structure

[16] Average production 235,000 t/year and energy consumption 6,830 MJ/$t_{ceramics}$ (UNIDO, 2016)

4.4 Controlled Dehumidification

4.4.1 Description of Baseline Situation and Energy Consumption

The current baseline situation for controlled dehumidification process has been presented in detail in Chapter 4.3.1.

4.4.2 Suggested Measures of Improvement

An advantage of using dehumidification kilns is the continuous recycling of heat within the kiln in lieu of heat discharging in the case of conventional kilns. The majority of water condenses on the coils of the dehumidifier and is removed as liquid rather than being ventilated to the outside of the kiln.

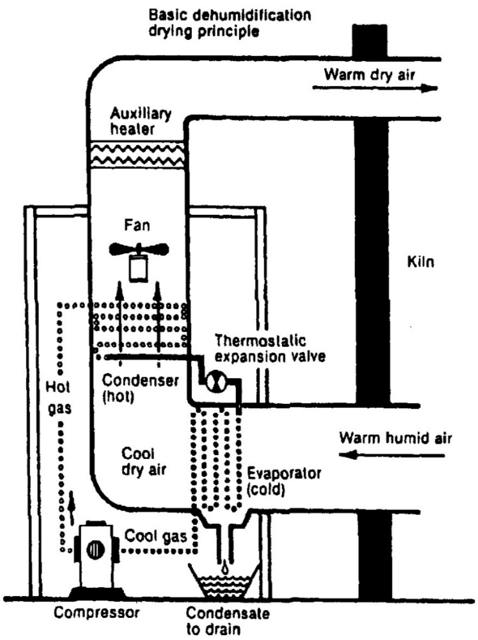
The key factors in drying ceramics are humidity and heat. Both must be strictly controlled to avoid rapid evaporation and steam generation.

Dehumidification is considered the best viable option for controlling the temperature in the drying process. Dehumidifiers essentially reduce the humidity of the accelerated air and keep it at a very low percentage. Controlled dehumidification during the drying process can accelerate the drying time period considerably. It also reduces downtime and reject rates, and makes the operating process time- and energy-efficient.

As it can be seen in figure 22, warm humid air flow which absorbed humidity in the drying chamber is forced through the cold coil of a compressor. As the air is cooled, its moisture condenses. This air is then heated to a specified temperature and fed into a drying chamber containing the material to be dried.

In the initial stages of ceramic drying, the most ideal case is if the air is hot, moist and under slight pressure so that it can flow evenly through the load. Once the chamber is heated to the required temperature (depending on the product from 60 to 200° C), forced convection fans inside the chamber move air through the load, and draft-inducing blowers pull ambient air through the chamber. As the temperature rises, the air loses some of its humidity, allowing the water content from the load to be taken up by the air. As the cycle progresses, more and more water is absorbed and removed by the air flow until drying is complete and the product is ready for firing.

Figure 23: Controlled Dehumidification Drying System



Source: (Hiziroglu, 2017)

4.4.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Although dehumidification kilns use electricity, which is more expensive than gas, they are still more economical than conventional kilns because they recycle heat. Using recycled heat contributes to energy saving, making dehumidification kilns more environment-friendly. It also has the advantage of reducing cracking or breaking in the kiln while firing, therefore preventing faulty products.

Table 13: Key Facts of Measure – Controlled Dehumidification

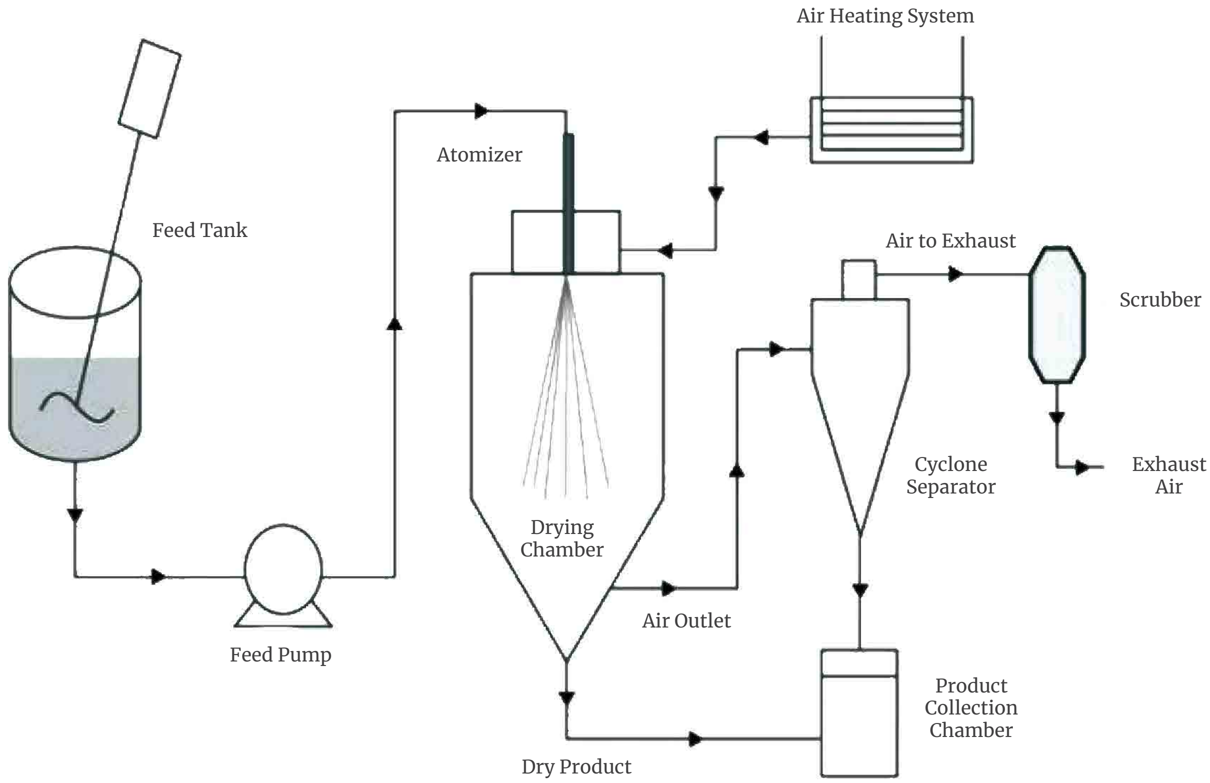
Key Facts of Measure – Controlled Dehumidification	
Investment Cost:	n.a., depending on specific intervention
Energy Savings: (thermal and electricity)	• Typical energy savings of 80% • 352 kWh/tonne
CO_2 Mitigation:	71 kg $CO_2/t_{ceramics}$
Advantage:	• Reducing cracking or breaking in the kiln while firing • Energy saving
Disadvantage:	• -

4.5 Exhaust Air Recirculation in Spray Dryers

4.5.1 Description of Baseline Situation and Energy Consumption

The spray drying process has been widely used for the production of particulate products in the ceramic industry. This process involves spraying of feed in the form of liquid or a slurry of nanoparticles into a drying chamber, drying of small droplets in contact with hot stream of the drying medium, and recovering powder product from the exhaust stream. The following figure shows a scheme of the spray drying process.

Figure 24: Schematic Representation of Spray-drying Mechanism. (1) Atomization. (2) Droplet-to-Particle Conversion. (3) Particle Collection,



Source: (Pignatello & Musumeci, 2018)

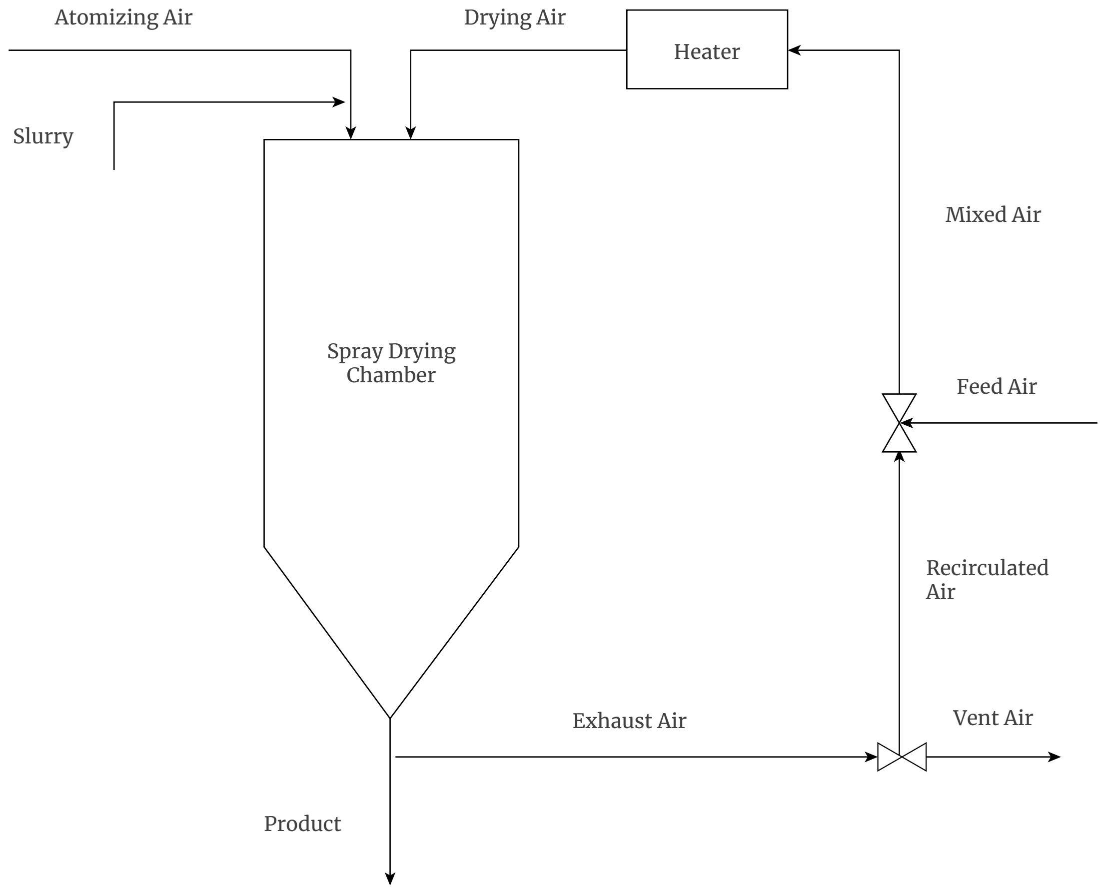
The mechanism of spray drying is based on the principle of eliminating moisture by using a heated atmosphere. The process may be described by three major phases: atomization, droplet-to-particle conversion, and particle collection, though some authors use four or five minor steps to describe it in more detail. As shown in the figure above, the slurry is pumped to an atomizer, which breaks up the liquid feed into a spray of fine droplets. Then, the droplets are ejected into a drying gas chamber where moisture vaporization occurs, resulting in the formation of dry particles. Finally, using an appropriate device, the dried particles are separated from the drying medium and then collected in a tank (Golman & Julklang, Simulation of exhaust gas heat recovery from a spray dryer, 2014).

This process is complex. It involves mass, heat, and momentum transfer between the droplet and drying medium as well as the heat and mass transfer in the partially dried agglomerate. This step requires a large amount of energy for evaporating the water in the slurry. According to the Reference Document on Best Available Techniques, the typical thermal energy consumption values for the spray drying process of wall and floor tiles are in the range of 980 - 2200 $kJ/kg_{product}$ (0.27 – 0.61 kWh/kg).

4.5.2 Suggested Measures of Improvement

The exhaust air of a spray dryer may be recycled into the process as drying air. An air preheater can be installed in the recirculation process to further use the waste heat from the exhaust air stream. During the recirculation process, the exhaust air stream is divided into a recirculated air stream and a vent air stream. The recirculated air stream is then mixed with ambient air to achieve the required drying air moisture content. The following figure shows the description of exhaust air recirculation in a spray dryer (Golman & Julklang, 2014).

Figure 25: Schematic Diagram of the Spray Drying System with Exhaust Air Recirculation



Adopted from (Golman & Julklang, 2014)

4.5.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Dryers with exhaust air recirculation can reduce the energy consumption in ceramic powder production by up to 60% compared to current practice. Different studies and simulations have shown that in order to improve the energy efficiency of the spray drying process, the recirculation ratio of exhaust air and slurry feed rate should be increased. At the same time, slurry concentration, inlet drying air temperature and drying air flow rate should be decreased. In other words, the process should operate at a low slurry feed rate, high slurry concentration, and high recirculation ratio of exhaust air.

Although the capital cost of adopting an exhaust heat recovery system is high (in Europe 1,500,000 EUR), the return on investment makes it lucrative. The capital cost includes the cost to purchase equipment, installation cost, material and labour costs (Ndimande, 2020).

Table 14: Key Facts of Measure – Exhaust Air Recirculation in Spray Dryers

Key Facts of Measure – Exhaust Air Recirculation in Spray Dryers	
Investment Cost:	1,500,000 EUR
Energy Savings: (thermal and electricity)	Decrease of up to 60% compared to current practice in thermal energy demand (264 $kWh/t_{product}$)
CO_2 Mitigation:	53 kg $CO_2/t_{ceramics}$
Advantage:	• High energy-saving potential • Simple modification
Disadvantage:	• High investment cost • Space requirement

4.6 Drying air preheating

4.6.1 Description of Baseline Situation and Energy Consumption

There are two different process steps which require drying: "Spray drying" and "Kiln drying". This energy efficiency measure can be applied to both drying processes, depending on subsector and degree of heat reusage (Szczeniak, Bauer, & Kober, 2020).The drying process is carried out at different temperatures based on the used technology. In tunnel dryers, temperatures range between 300-350 °C, while the temperatures in vertical dryers are within the range of 200-220 °C (UNIDO, 2016).

The baseline situation for this measure is a drying process without preheating. The drying process requires up to 30%[17] of the total fuel consumption, which corresponds to appr. 2,000 MJ or $580 kWh/t_{product}$[18] (Parsons Brinckerhoff, WSP, DNV GL, 2015).

4.6.2 Suggested Measures of Improvement

As an alternative to direct hot air recycling (chapter 4.5), the system could be upgraded with air-gas heat exchangers at the exhaust gas streams and/or the hot air streams from the cooling zone of kilns. A typical air preheater type used for this application is a heat pipe heat exchanger, because of its associated with high heat transfer capability and economic viability (Miguel Castro Oliveira, 2020).

Figure 26 shows the shares of total fuel consumption of different energy consuming processes in the brickworks production The majority of the fuel is utilised in the kiln and the dryer. Often heat recovery is used to recycle cooling air from the kiln to the dryer. Mainly the exhaust gases from the kiln are used for heat recovery at high temperature. Due to its high moisture content and low temperature level, heat recovery from the dryer exhaust air is quite difficult to realize (Parsons Brinckerhoff, WSP, DNV GL, 2015).

Figure 26: Typical Energy Breakdown of Brickworks Production Showing Heat Recovery from the Kiln to the Dryer

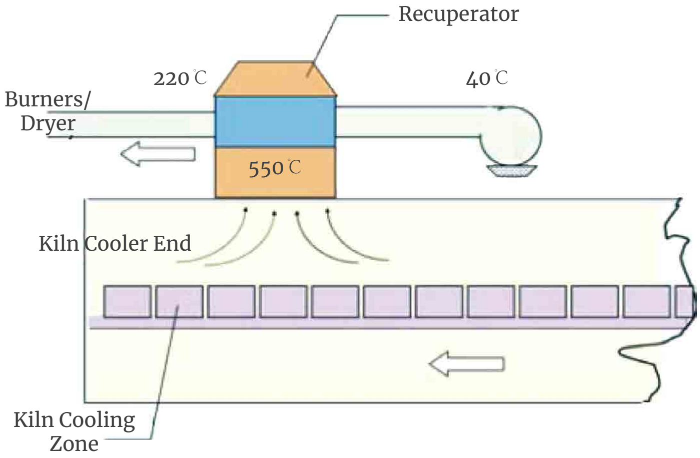
Source: (Parsons Brinckerhoff, WSP, DNV GL, 2015)

17 (UNIDO, 2016)
18 Average production 235,000 t/year & average thermal energy 6,140 MJ/t (UNIDO, 2016)

Using flue gases requires suitable heat exchangers. The sophisticated design of large modern kilns needs to be optimized and maintained to the correct operating conditions to be able to implement heat exchangers in the exhaust air stream (Szczeniak, Bauer, & Kober, 2020).

For example, the heat recovery system, shown in the figure below, can be implemented in the cooling zone. The 550 °C hot air from the end of the kiln cooler is used in a recuperator to preheat the supply air for drying process (SIDBI, 2019).

Figure 27: Heat Recovery System Ceramic Kiln



Source: (SIDBI, 2019)

4.6.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Using the combustion heat regeneratively as described above would typically cost around 3,000,000 EUR per site. As a result, CO_2 emissions can be reduced by 7 % – 20 % (Szczeniak, Bauer, & Kober, 2020). The fuel saving potential is about 110,000 m³ fuel/year (Miguel Castro Oliveira, 2020). Taking into account a typical production volume of 235,000 t/year and the average thermal energy consumption of 6,140 MJ/t, fuel savings of 25 % can be achieved (UNIDO, 2016). Realistically, one can expect a reduction in total thermal energy of 10 %. The average electrical energy demand will double due to the additional air fans.

Table 15: Key Facts of Measure – Drying Air Preheating

Key Facts of Measure – Drying Air Preheating[19]	
Investment Cost:	13 EURO /$t_{ceramics}$
Energy Savings: (thermal and electricity)	• 613 MJ/$t_{ceramics}$ (170 kWh/t) decrease of thermal energy demand • 7 kWh/ $t_{ceramics}$ increase of electrical energy demand
CO_2 Mitigation:	30 kg CO_2/$t_{ceramics}$
Advantage:	• Higher recuperation rate than direct hot air recycling
Disadvantage:	• Requires suitable heat exchangers

[17] Average production 235,000 t/year and energy consumption 6,830 MJ/$t_{ceramics}$ (UNIDO, 2016)

4.7 High-Efficiency Burners

4.7.1 Description of Baseline Situation and Energy Consumption

As already mentioned, kiln firing is a key process, and the largest energy consumer, in ceramics production. It controls many important properties of the finished product. These include mechanical strength, abrasion resistance, dimensional stability, resistance to water and chemicals, and fire resistance. Main fuels are natural gas and fuel oil. In some cases, solid fuels, biogas/biomass and electric power are also used for heat generation. The following table shows the specific energy consumption (unit energy consumption) for drying and firing in two different kiln types:

Table 16: Specific Energy Consumption (Drying and Firing) in Continuous Kilns

Kiln	Unit	SEC Product		
		Clay Block	Facing Bricks	Roof Tiles
Fast Firing Tunnel Kilns	kJ/kg	1,250-3,500	1,590-4,500	2,930-4,605
	kWh/kg	0.35-0.97	0.44-1.25	0.87-1.28
Tunnel Kilns	kJ/kg	1,000-2,500	1,600-3,000	1,600-3,500
	kWh/kg	0.28-0.69	0.44-0.83	0.44-0.97

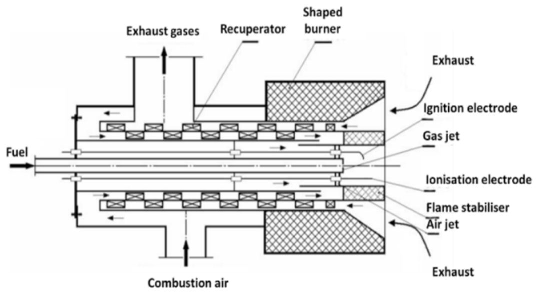
Source: (European Commission, 2007)

4.7.2 Suggested Measures of Improvement

Modern, highly-efficient burners allow preheating of the combustion air with exhaust gases (examples include self-recuperative and regenerative burners). These burners can replace old burners in ceramic tunnel kilns and roller kilns, thereby reducing fuel consumption.

Heat exchangers used in such burner systems are built with highly-conductive materials, such as silicon carbide (SiC), and equipped with grooves and fins. They are interposed between opposite flows of cold air and hot exhausts. Self-recuperative burners are standardized and pre-assembled products, and therefore much cheaper than a single external exchanger that requires a specific realization. Furthermore, during maintenance or in case of problems, only one single burner has to be stopped while the rest of the oven can continue to operate. Self-recuperative radiant tube burners also reduce the wasted heat considerably.

Figure 28: Left - Description of EPR-300-diffusive Self-recuperative Burner



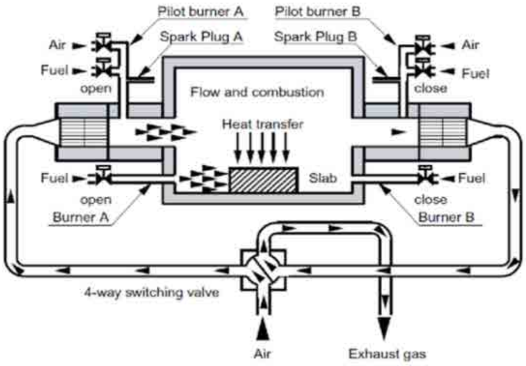
Source: (Rozpondek & Wnęk, 2010)

Right - Radiant Tube Self-recuperative Burner

Source: (ESA S.p.A., 2021)

Other types of highly-efficient burners are regenerative burners. These burners use an intense recycling technique of flue gases to preheat the combustion air. Regenerative burners utilise a system based on pairs of burners. These burners exchange heat through a medium, receiving and transferring heat during alternating cycles of air suction and ejection of exhaust gases. The mediator, or "regenerative bed", is a tank that is normally filled with ceramic material of different shapes and types.

Figure 29: Left - Description of a Regenerative Burner



Source: (Elmabrouk, 2011)

Right – REGEMAT Regenerative Burner

Source: (CRUX Thermal, 2021)

4.7.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Implementing this measure can result in firing efficiency improvement by approximately 10 %, fuel savings of 25 % – 30% in self-recuperative burners and 50 % – 60 % in regenerative burners (ESA Pyronics International, 2015) (Tangjitsicharoen, Ratanakuakangwan, Khonmeak, & Fuangworawong, 2013).

The self-recuperative burners integrate a heat exchanger that uses the enthalpy of the flue gases to preheat the combustion air, reducing consumption and emissions of CO_2 and NO_x even by 30 % compared to the use of cold air.

Table 17: Key Facts of Measure – High-efficiency Burners

Key Facts of Measure – High-efficiency Burners	
Investment Cost:	n.a. (asked seller for quotation)
Energy Savings: (thermal and electricity)	Fuel savings of 25–30% in self-recuperative burners and 50–60% in regenerative burners • Self-recuperative burners 351 kWh/t • Regenerative burners 702 kWh/t
CO_2 Mitigation:	Up to 30% reduction (on average 106 kg CO_2/t)
Advantage:	• Energy saving • Reduces fuel consumption • Reduces CO_2 and NO_x emission (self-recuperative burners) • Reduce the heat loss
Disadvantage:	• -

4.8 Low Thermal Mass Kiln Cars and Furniture

4.8.1 Description of Baseline Situation and Energy Consumption

Kiln furniture and cars are used to carry and transport the products in the furnace during the thermal treatment / sintering process. Depending on the specific application, the kiln furniture (and kiln cars) can add up to 80 % of the total mass of the kiln charge. (Noeth & Neubauer, 2017). More specifically, the mass ratio of kiln furniture to ware (ceramics), is around 4:1 for most tableware, 6:1 for porcelain and 6:1 or higher for sanitary ware. (Agrafiotis & Tsoutsos, 2001). As both the ceramic material and anything else in the kiln need to be heated up to the required temperature, this leads to considerable (partly unproductive) energy consumption and long process cycles.

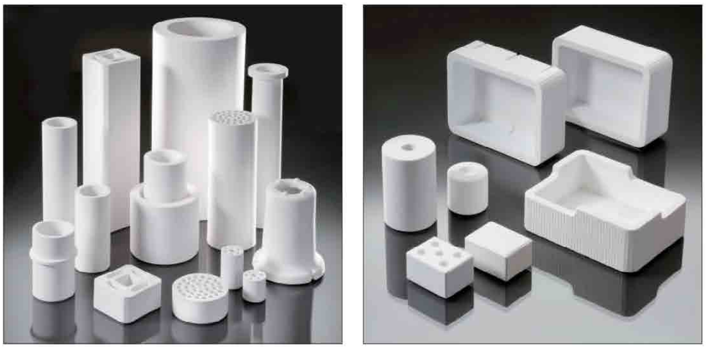
4.8.2 Suggested Measures of Improvement

In principle, there are two possibilities to reduce the thermal mass of the kiln cars and the furniture: a design approach and a material approach. These include the following options:

- Thinner walls,
- Increasing the porosity,
- Combining different materials,
- Improving the high temperature properties of the materials used.

However, there is a trade-off between minimum deformation of the materials at high temperature and the reduction of the mass of the furniture materials. One example for promising product design are alumina and mullite-based kiln furniture materials components[20]. These show promising product performances and are depicted below. The total weight reduction for such materials ranges between 20 % and 50 % while still keeping or even improving the material's technical properties (Noeth & Neubauer, 2017).

Figure 30: Examples for RAMUL Components (left) and RAKOR Saggars and Firing Props



Source: (Noeth & Neubauer, 2017)

A different approach achieved a weight reduction of kiln cars by 17 % (from 1186 kg to 983 kg) by reconstructing the car with improved insulating materials such as ultralite[21] and hollow bricks. Moreover, refractory bricks were replaced by hollow ceramic coated pipes at the supporting pillars for holding the racks. Total fuel savings are estimated at 10 %-13 % per cycle. This measure can be applied for all kiln cars used in tunnel and shuttle kilns. (GEF-UNIDO-BEE-PMU Bureau of Energy Efficiency; Patna Ceramic, 2021)

An example of replacing solid cordierite shelves by light weight extruded cordierite batts is shown in the figure below.

[20] designed by Paul Rauschert Steinbach GmbH and Fraunhofer Center for high Temperature Materials and Design HTL
[21] An improved insulated material

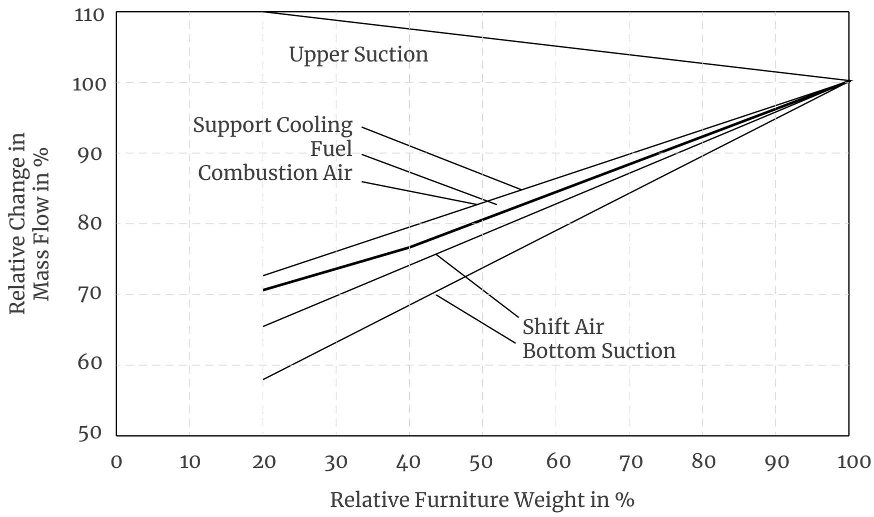
Figure 31: Typical Plate (left) and Light Weight Version (right)

Source: (GCPC ENVIS RP, 2021)

4.8.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

The following chart shows the correlation between the relative furniture weight and the corresponding changes in necessary fuel, cooling requirement and combustion air requirement. Analysis shows that a reduction of furniture weight by 80 % (i.e., overall reduction of furniture and kiln car by 35 %) leads to energy savings of almost 30 %. (Redemann, 2019)

Figure 32: Changes of Mass Flows Depending on Furniture Weight



Adapted from: (Redemann, 2019)

Table 18: Key Facts of Measure – Low Thermal Mass Kiln Cars and Furniture

Key Facts of Measure – Low Thermal Mass Kiln Cars and Furniture	
Investment Cost:	1,500,000 – 2,000,000 EUR per site (depending on sub-sector) (Szczeniak, Bauer, & Kober, 2020)
Energy Savings: (thermal)	• Assumption: 20 % thermal energy saving • Example for tiles production: appr. 780 MJ/$t_{ceramics}$ (220 kWh/t) decrease of thermal energy demand[22]
CO_2 Mitigation:	5 % - 20 % emission reduction (t CO_2) (Szczeniak, Bauer, & Kober, 2020), average 44 kg CO_2/ $t_{ceramics}$
Advantage:	• Lower running costs, repairs, downtime and maintenance
Disadvantage:	• In case of material change: thermal properties need to be evaluated

[22] Own calculation, based on assumption of 20% saving and 3.92 GJ/t thermal energy consumption for tiles

4.9 Electric Kiln and Drying

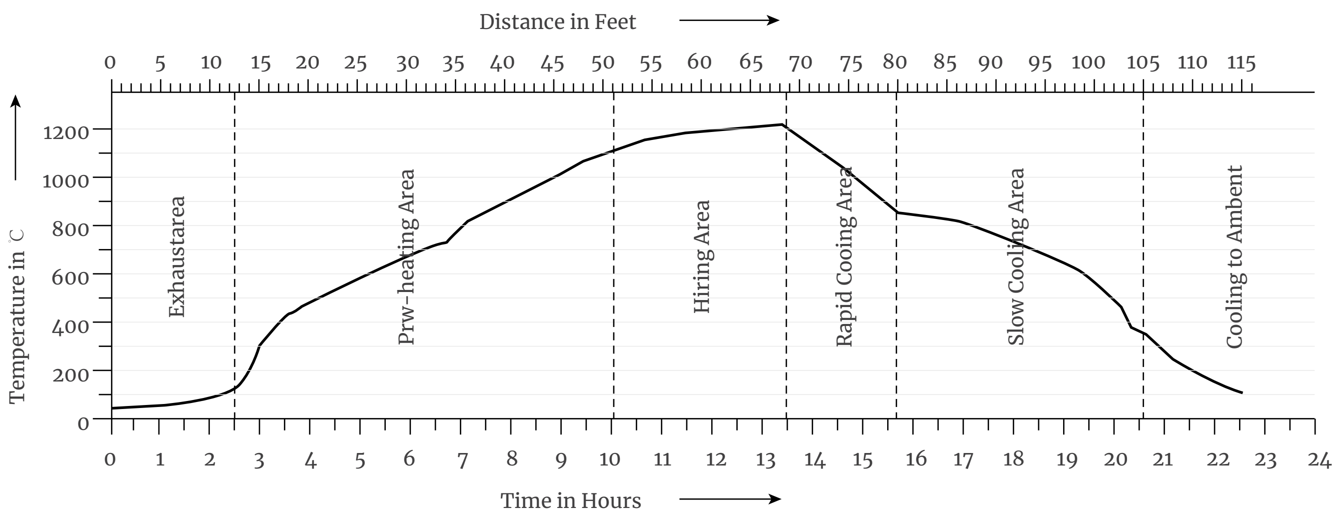
4.9.1 Description of Baseline Situation and Energy Consumption

In the ceramic industry, two classes of kilns are used:

Continuous Kilns

- The product travels at a low speed through the kiln, which is up to 10 m wide by 5 m high, with a length varying from 60 to 200 meters. While the product passes through the different zones, the temperature is increasing up to the temperature peak, followed by a controlled profile of cooling. Figure 33 shows the optimum firing cycle for a tunnel kiln (Parsons Brinckerhoff, WSP, DNV GL, 2015).

Figure 33: Optimum Firing Schedule for Tunnel Kiln



Source: (SIDBI, 2019)

Batch Kilns

- In this kind of a kiln, the ware runs through the firing cycle in an insulated enclosure with doors. Such kilns may vary in size from table-top kiln to room sized production kilns, which are loaded, fired and unloaded. The duration of the firing process depends on the size and thickness of the product and can take between a few hours up to a week (Parsons Brinckerhoff, WSP, DNV GL, 2015).

[23] For an average production 235,000 t/year & average thermal energy 6,140 MJ/t (UNIDO, 2016)

The following facts summarize the baseline situation for both types of kilns:

- Typically, thermal energy is provided by fuel combustion (Parsons Brinckerhoff, WSP, DNV GL, 2015).
- The firing process in roller hearth kilns, tunnel kiln or periodically operated kilns can be single, double or even triple. For the firing process, a temperature between 1050-1150 °C is needed. Tunnel kilns require a firing time of 20 to 50 hours, whereas in modern hearth kilns it takes only 1 to 2 hours (SIDBI, 2019).
- The proportion of total energy consumption for the kiln and drying processes is 90 %, which corresponds to 6,140 MJ/$t_{ceramics}$ (1,705 kWh)[23].

4.9.2 Suggested Measures of Improvement

One option to decarbonize the process is to replace energy from fossil fuels with low carbon electricity, i.e., to switch to electric kilns and electric drying. However, no large-scale continuous kiln designs which meet the needs of the ceramic sector are currently available. A large-scale continuous electric kiln will require significant development and collaboration with manufacturers to invent and produce a suitable design for widespread application. The overall emission savings depend on used electrical mix onsite (Parsons Brinckerhoff, WSP, DNV GL, 2015).

4.9.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Upgrading to a large electric kiln and dryer would cost around 23,000,000 EUR per site in Europe. As a result, the total thermal energy consumption can be reduced to almost zero. When purchasing a low-carbon electricity mix, electricity consumption might increase more than six times, but CO_2 emissions can be reduced by 80 % (Szczeniak, Bauer, & Kober, 2020).

The actual amount of reduced CO_2 emissions from these measures heavily depends on the emission factor of the electricity mix. Due to the increase of electrical energy consumption, it is recommended to install a photovoltaic system at the production site.

Table 19: Key Facts of Measure – Electric Kiln and Drying

Key Facts of Measure – Electric Kiln and Drying	
Investment Cost:	100 EURO /$t_{ceramics}$
Energy Savings: (thermal and electricity)	• 6,140 MJ/$t_{ceramics}$ (1,706 kWh/t) decrease of thermal energy demand • 1,535 kWh/ $t_{ceramics}$ increase of electrical energy demand
CO_2 Mitigation:	• Based on assumptions currently negative – • appr. -600 kg CO_2/$t_{ceramics}$
Advantage:	• Reduces final energy consumption • Potential of considerable CO_2 reduction
Disadvantage:	• Higher electric energy consumption • High investment costs • No design of large-scale continuous kiln available yet

4.10 Microwave Assisted Firing and Drying

4.10.1 Description of Baseline Situation and Energy Consumption

The current baseline situation for the firing and drying process has been presented in detail in Chapter 4.9.1.

4.10.2 Suggested Measures of Improvement

The sintering process (firing and drying) of ceramic ware is a critical step for the quality of the final product. The heavy loads of the large-scale kilns have a negative effect on heat transfer from the outside to the middle of the desired product. The temperature gradients lead to stresses and damages in the material (European Commission, 2007).

Studies have shown that applying microwave energy during the firing of ceramic ware leads to more evenly-distribution of heat from the outside to the centre of the units. Undue heat losses to the kiln structure can be avoided by combining microwave energy and conventional heating such as gas or electrical energy (European Commission, 2007).

Currently, microwave-assisted technology is used only in batch kilns. For large-scale continuous kilns, this technology is still experimental, but bears significant benefits:

- Minimized thermal stresses throughout the firing cycle,
- Considerably increased product throughputs, i.e., much shorter firing cycles,
- Significantly reduced energy consumption for firing– but there may be less excess heat available for drying purposes,
- Reduced solid process losses/solid waste,
- Improved quality, including significant gain in mechanical properties,
- Enhanced binder removal (from refractory products),
- Reduced emissions due to reduced energy consumption and higher throughput,
- Lower fluoride emissions – which are closely related to the time the product spends above 800 ºC.

This process is currently neither economically nor technically mature: Technical problems, including safety aspects, need to be solved before it can be used in full-scale applications. From economical perspective, the process requires a high demand of electrical energy (European Commission, 2007).

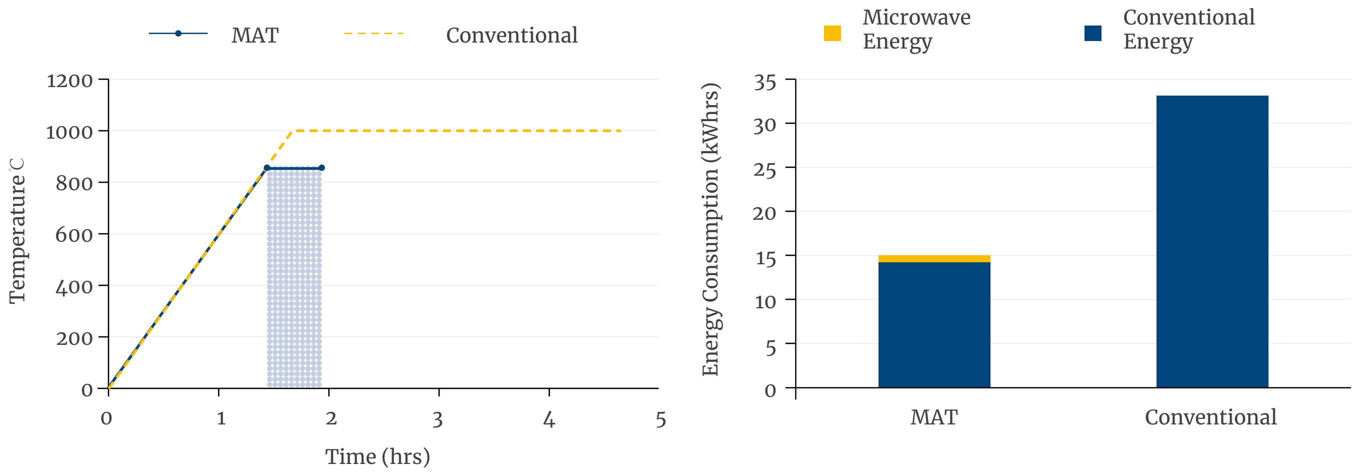
Microwave energy can, in principle, also be used for drying ceramic ware. The advantages and disadvantages, as listed above for firing, also apply for drying processes with microwave ovens. Research shows that microwave assisted drying is not applicable for complex product shapes but only for thin shapes (European Commission, 2007).

4.10.3 Potential Energy Savings and Greenhouse Gas Emission Reduction

Fuel savings can be achieved through reducing firing time by eight times and drying time by 7 - 30 times (Miguel Castro Oliveira, 2020). This way, energy savings of up to 50 % were achieved for a series of ceramic products in pilot scale kilns via a combination of natural gas and microwaves firing (MAGF)). This approach cuts both production time and fluoride emissions – both major issues in today’s production (DTI, 2017).

According to a study of Shulman (2007), this technique is especially suitable for fine grained ceramics and significantly reduces energy use. As visualised in Figure 34, the energy requirements while using microwave assisted technology (MAT) are less than 50 % of those for conventional heating. The main reason for this difference is the duration of the firing process, which is less than two hours for using MAT and nearly five hours for conventional heating.

Figure 34: On the Left the Temperature and Duration of the Firing Process and on the Right the Total Energy Consumption



Source: (Shulman, 2007)

Based on the studies mentioned above, we estimate thermal energy savings of 50 % and an increase in electrical energy of 5%. The investment costs cannot be estimated for large scale plants due to their experimental status.

Table 20: Key Facts of Measure – Microwave Assisted Firing and Drying

Key Facts of Measure – Microwave Assisted Firing and Drying[24]	
Investment Cost:	n.a.
Energy Savings: (thermal and electricity)	• 3,070 MJ/$t_{ceramics}$ (853 kWh/t) decrease of thermal energy demand • 85 kWh/ $t_{ceramics}$ increase of electrical energy demand
CO_2 Mitigation:	120 kg CO_2/$t_{ceramics}$
Advantage:[25]	• Finer microstructure • Improved mechanical properties • Lower processing times and energy consumption
Disadvantage:	• Technical problems • Safety aspects • High electrical energy costs • Future technology still needs development

[24] Average production 235,000 t/year and energy consumption 6,830 MJ/$_{tceramics}$ (UNIDO, 2016)
[25] (Borrell & Salvador, 2018); (European Commission, 2007)

4.11 Outlook on Further Developments

As per the agreed decarbonization path of the European Union[26], one of the greatest challenges in the upcoming years is certainly the **reduction of CO_2 emissions in industrial production**. The ceramic sector is highly heterogenous, with products ranging from floor and roof tiles over to table and sanitary ware to technical ceramics. In this sector, about **16 % of overall CO_2 emissions are process emissions** inherent in the breakdown of the used materials (limestone, dolomite or magnesite). The majority of emissions (around 66 %) stem from the combustion of fossil fuels. Besides the measures described in this report, this means that switching to low-carbon fuels is one major field for reducing GHG emissions. However, the switch from fuel combustion to electrified kilns only leads to overall GHG savings in cases where low-carbon electricity can be supplied.

Another option is the replacement of natural gas by biogas or syngas from biomass or waste. This option requires retrofitting of existing kilns and currently has the disadvantage of biogas being 2-3 times more expensive than natural gas. (CeramUnie, 2012) . There is also the option to implement an onsite biomass gasifier which converts biomass into fuel and substitutes fossil fuels. Figures provided in a study performed in the United Kingdom (Parsons Brinckerhoff, WSP, DNV GL, 2015) point at CAPEX of around 17 million EUR and emission reductions of 29 % in the heavy clay sector.

Apart from the options targeting at the improvement of the process itself, end of pipe technologies such as **carbon capture and storage (CCS)** are expected to play a major role in further CO_2 emission scenarios with reduction potentials between 50 % and 90 %. However, application in the ceramics sector is currently limited due to the comparatively small size of companies compared to other applications such as in the cement sector. (Axelson, Robson, Wyns, & Khandekar, 2018)

CO_2 can be captured at the chimney of kiln plants, either to store it for the long-term **(carbon capture and storage - CCS)** or to use it for another purpose later on **(carbon capture and utilization - CCU)**.

Two major technologies are currently being investigated: Post-combustion and oxy-fuel technology. For more details on these technologies, refer to report "Energy Efficiency in the Cement Industry – Technical Guidelines on Energy Efficiency in Major Energy-Consuming Sectors".

[26] Aim of climate neutrality by 2050 (net-zero greenhouse gas emissions) – refer to the European Green Deal and EU's commitment under the Paris Agreement. (https://ec.europa.eu/clima/policies/strategies/2050_en) .

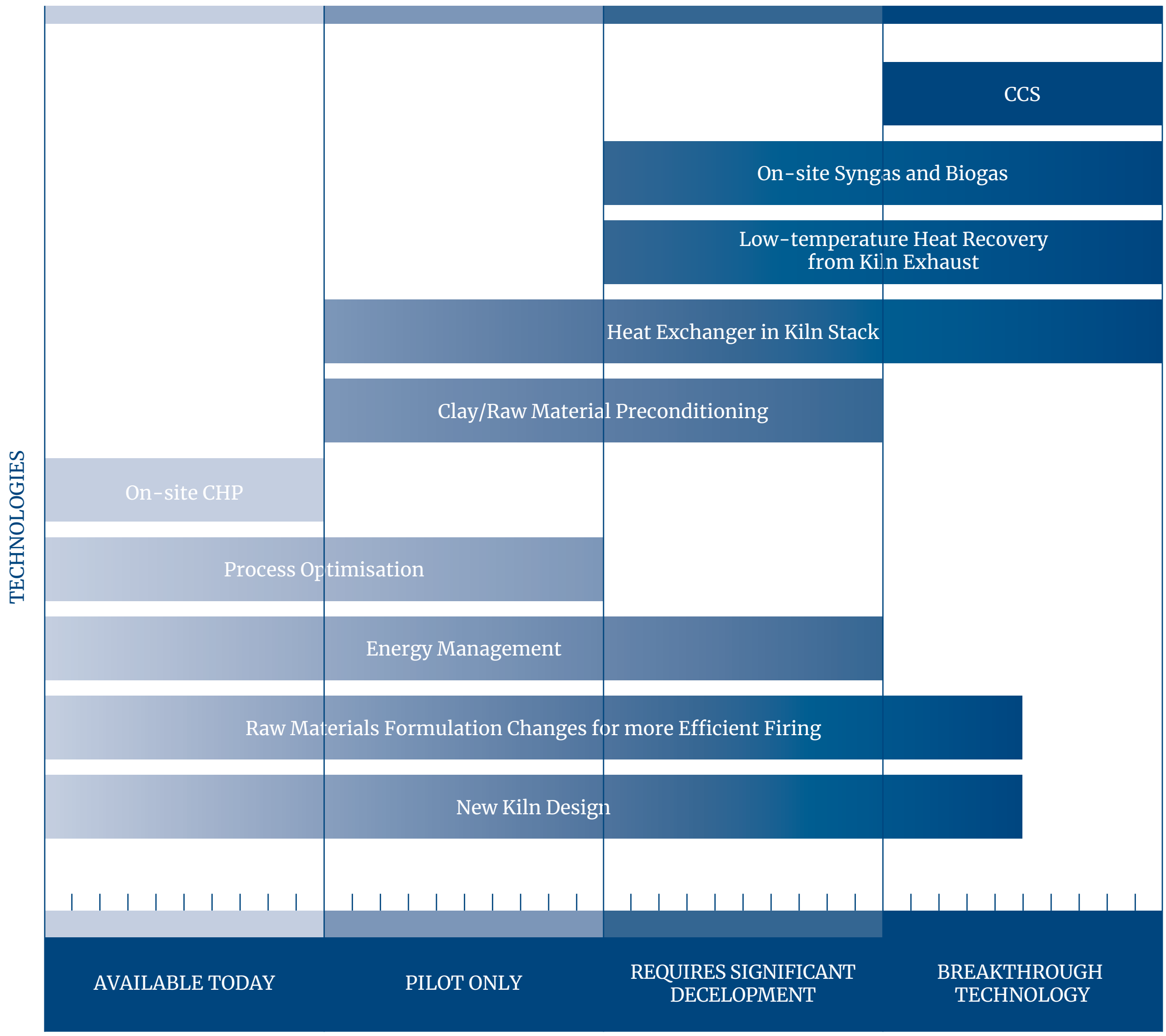
5 Conclusions

Ceramics production is a highly energy-intensive process and comprises a wide range of products, with energy requirements ranging from less than 1 MWh (brick and roof tiles) to 14 MWh (technical ceramics) per tonne of product. 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 CO_2 emissions.

Although lower than in other sectors like for cement, process emissions still account for 16 % of overall emissions. Thus, the CO_2 reduction potential via optimization of thermal and electrical efficiency is limited. Optimizing the largest consumer stages – the drying and firing process – have been described in detail and can lead to considerable savings within these sub-processes (ranging from appr. 130 to 700kWh/$t_{product}$). Further energy conservation potential lies in product design and fuel changes.

In the long run, major contributions to CO_2 reduction are expected from carbon capture technologies and from the use of on-site syngas and biogas (CeramUnie, 2012).

Figure 35: Contributions to Global CO_2 Reductions

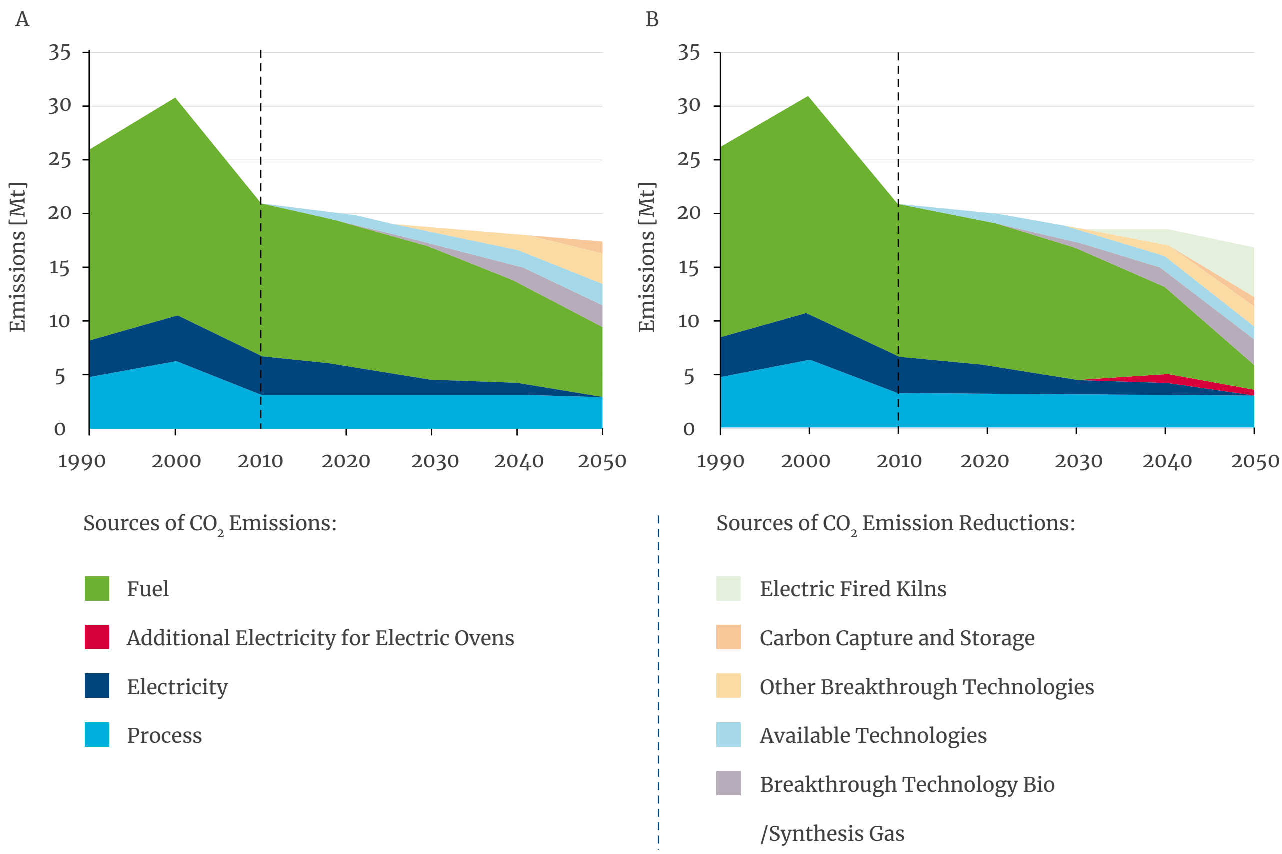


Source: (CeramUnie, 2012)

The CO_2 reduction path for the European ceramic industry developed by CeramUnie shows a potential reduction of emissions from 1990 until 2050 by up to 65 %. An underlying assumption of the model, which is based on all currently available technologies, is that all obstacles for the use of alternative fuels can be removed. Another assumption is that in the period 2030-2050, half of all kilns in Europe are switched to electricity or syngas/biogas (with additional natural gas firing). In comparison to 1990 levels, CO_2 emissions can be reduced by up to 78 %. Zero Emissions are not feasible due to process emissions. (CeramUnie, 2012)

The following chart depicts the assumed shares of CO_2 emissions and emission reductions for the European ceramic industry:

Figure 36: CO_2 Reduction Path Ceramic Industry (with/out Electric Kilns)



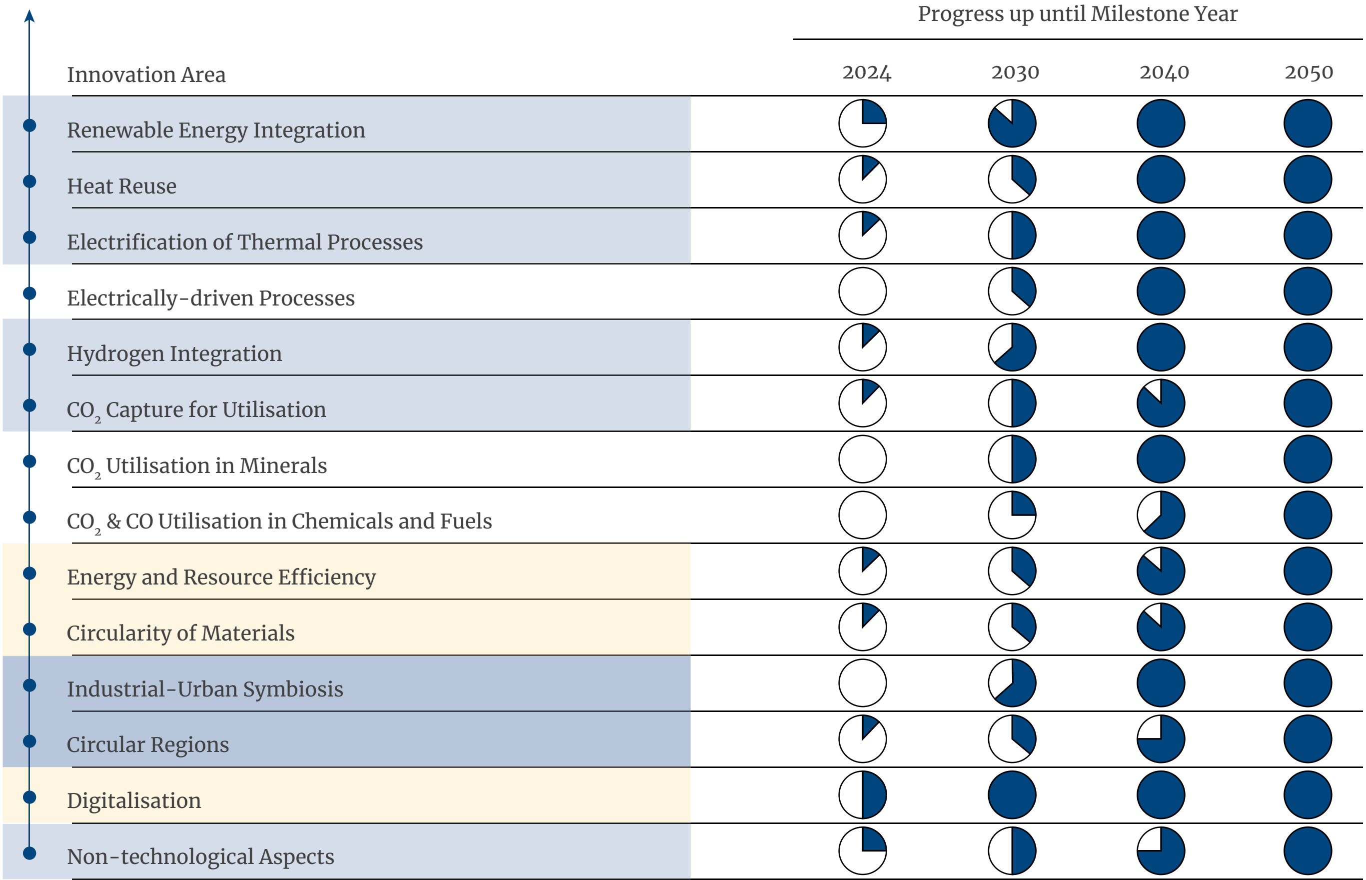
adapted/translated from: (CeramUnie, 2012)

A presentation held at the "European Ceramic Days 2020", which targeted process industries and SMEs on their way to Green Economies, underlined that all identified ways to reduce carbon intensity and environmental impact need to be realized in order to achieve the reduction goals until 2050.

This is graphically depicted in circles showing the progress performance[27]. Until 2040/2050 all types of measures/innovation areas must be fully exploited to reach the decarbonization targets.

[27] Fully coloured circles mean full realisation, white circles mean no realisation; partly realisation is shown by partly coloured circles. More specifically, progress is depicted as a percentage of (TRL 9) projects planned or of investment needs until 2050 (for the areas circular regions, digitalisation and non-technological aspects). TRL evaluate he development status of new technologies on the basis of a systematic analysis. It indicates how advanced a technology is on a scale from 1 to 9.

Figure 37: Innovation Areas for Carbon Reduction



Source: (Orduña, 2020)

The most promising established energy saving measures have been presented throughout the report and are summarized below.

Measures	Key Facts of Measures				
	Investment Cost	**Energy Savings (thermal and Electricity)**	**CO_2 Mitigation**	**Advantage**	**Disadvantage**
Use of Dry Route for Raw Material Preparation	Maintenance cost savings 2.5€/tonne and personnel 2 instead of 3 people (Kocak & Karasu, 2018)	• 1274 MJ/$t_{ceramics}$ (354 kWh/t) decrease of thermal energy demand • 19 kWh/ $t_{ceramics}$ decrease of electrical energy demand	83 kg $CO_2/t_{ceramics}$	• No need for drying power • Less media and lining war than wet milling • Less shrinkage • Start/stop at any time	• More dust compared to wet route • Wet route offers narrower particle size and better homogenisation
Improvements at Ceramic Design	n.a. (depending on specific intervention), e.g. savings due to reduced temperature of 200°C => specific energy consumption reduced by appr. 15% (670 kWh/t for sanitary ware, 135 kg CO_2/t)			• Energy saving due to reduced firing temperature • Higher material porosity, more water absorption • Change in design/form – lower material costs with comparable product characteristics	• -
Airless Drying	n.a., depending on specific intervention	557 MJ/$t_{ceramics}$ (155 kWh/t) decrease of thermal energy demand	31 kg $CO_2/t_{ceramics}$	• Environmental and operational benefits • Better regulation of drying process	• More complicated process structure
Controlled Dehumidification	n.a., depending on specific intervention	• Typical energy savings of 80% • 352 kWh/tonne	71 kg $CO_2/t_{ceramics}$	• Reducing cracking or breaking in the kiln while firing • Energy saving	• -
Exhaust Air Recirculation in Spray Dryers	1,500,000 EUR	Decrease of up to 60% compared to current practice in thermal energy demand (264 kWh/tproduct)	53 kg $CO_2/t_{ceramics}$	• High energy-saving potential • Simple modification	• High investment cost • Space requirement
Drying Air Preheating	13 EURO /$t_{ceramics}$	• 613 MJ/$t_{ceramics}$ (170 kWh/t) decrease of thermal energy demand • 7 kWh/ $t_{ceramics}$ increase of electrical energy demand	30 kg $CO_2/t_{ceramics}$	• Higher recuperation rate than direct hot air recycling	• Requires suitable heat exchangers

Measures	Key Facts of Measures				
	Investment Cost	Energy Savings (thermal and Electricity)	CO_2 Mitigation	Advantage	Disadvantage
High-efficiency Burners	n.a. (asked seller for quotation)	• Fuel savings of 25–30% in self-recuperative burners and 50–60% in regenerative burners • Self-recuperative burners 351 kWh/t • Regenerative burners 702 kWh/t	Up to 30% reduction (on average 106 kg CO_2/t)	• Energy saving • Reduces fuel consumption • Reduces CO_2 and NOx emission	• -
Low Thermal Mass Kiln Cars and Furniture	1,500,000 – 2,000,000 EUR per site (depending on sub-sector) (Szczeniak, Bauer, & Kober, 2020)	• Assumption: 20 % thermal energy saving • Example for tiles production: appr. 780 MJ/$t_{ceramics}$ (220 kWh/t) decrease of thermal energy demand(Thermal)	5 % - 20 % emission reduction (t CO_2) (Szczeniak, Bauer, & Kober, 2020), average 44 kg CO_2/ $t_{ceramics}$	Lower running costs, repairs, downtime and maintenance	• In case of material change: thermal properties need to be evaluated
Electric Kiln and Drying	100 EURO /$t_{ceramics}$	• 6,140 MJ/$t_{ceramics}$ (1,706 kWh/t) decrease of thermal energy demand • 1,535 kWh/ $t_{ceramics}$ increase of electrical energy demand	• Based on assumptions currently negative – • appr. -600 kg CO_2/$t_{ceramics}$	• Reduces final energy consumption • Potential of considerable CO_2 reduction	• Higher electric energy consumption • High investment costs • No design of large-scale continuous kiln available yet
Microwave-assisted Firing and Drying	n.a.	• 3,070 MJ/$t_{ceramics}$ (853 kWh/t) decrease of thermal energy demand • 85 kWh/ $t_{ceramics}$ increase of electrical energy demand	120 kg CO_2/$t_{ceramics}$	• Finer microstructure • Improved mechanical properties • Lower processing times and energy consumption	• Technical problems • Safety aspects • High electrical energy costs • Future technology still needs development

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