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Technical Report

A-2016/1039

Evaluation of the energy performance of cement kilns in the context of co-processing

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Executive Summary

Purpose of this study

Cement clinker production in modern cement plants is agreed to be a highly efficient process. However, the benefits of the process by far exceed the aspect of energy efficiency. Due to the unique process features, fuel ashes (fossil and alternative) are entirely recycled by being incorporated into the cement clinker contributing to resource efficiency.

This study was conducted to illustrate the opportunities and challenges of the cement production process regarding the co-processing of alternative fuels. It is based on the fact that a distinction has to be made between energy demand and energy efficient production. While the mere calculation of energy efficiency of cement kilns remains important and necessary, a broader view reflects energy recovery, material recycling, fuel quality and actual and potential recovery of waste heat.

Approach

To highlight the benefits of co-processing in cement kilns, a guideline to evaluate the energy performance of cement production facilities has been developed and an adequate energy performance index has been proposed. It considers the specific requirements and circumstances of cement clinker production and was calculated to be in a range of 70% to 80% for the CEMBUREAU members (reference year: 2014).

Based on process modelling of optimised kilns, different fuel and raw material moisture scenarios were investigated presenting a range of energy performance.

Typical fuels co-processed were characterised regarding properties and their usefulness for the clinker burning process both for energy and material contents taking into account possible pre-treatment measures.

Three examples highlight the potential of waste heat recovery in addition to the process integrated raw material drying.

Based on the findings, the study concludes with considerations on the role of co-processing in a circular economy.

Key findings

- The energy demand of the production process depends predominantly on individual circumstances, mainly the local raw material moisture and the individual plant layout. However, it does not give any information on the energy performance of the plant. Installations are designed to dry the local raw material recovering waste heat from the process. Plants with a high raw material moisture content exhibit a higher specific energy demand. But since more energy is utilised for raw material drying, the energy performance may be even higher.
- Further waste heat recovery in other drying processes (mineral components for cement production, alternative fuels) for electricity generation or heat export (e.g. district heating) may increase the energy performance where feasible from a technical and economical point of view.
- The specific characteristics of the fuels used have an impact on the overall energy demand. An increase in alternative fuel use – depending on the respective fuel

properties – may lead to a moderate increase in the specific energy demand but also increases the potential for the application of further waste heat recovery measures.

- All fuel ashes are incorporated into the cement clinker and in that way become part of the product. The combination of simultaneous energy recovery and material recycling is unique to co-processing. But it implicates that the ash composition needs to give an added value to the process matching the raw material composition to meet the high product quality. Furthermore, the energy content of the fuel mix is required to meet certain demands of the process. High substitution rates of fossil fuels by alternative fuels can only be achieved with a comprehensive pre-treatment as well as with a quality surveillance of the alternative fuels.
- If the requirements are met, co-processing in cement kilns can contribute to the development of a sustainable and future oriented circular economy. Along with a step-by-step reduction of landfilling, waste fuels that cannot be used as a resource for co-processing need to be used in dedicated waste incineration facilities and waste-to energy plants.

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1 Introduction

The cement production process is agreed to be highly energy efficient due to its specific characteristics. But there are further aspects to take into consideration. The unique feature of the process is the combination of simultaneous energy recovery and material recycling from regular fossil fuels and especially alternative fuels by co-processing. Furthermore, an essential feature of the burning process is the integrated drying of raw materials that recovers a considerable amount of waste heat from the burning process.

To highlight these advantages of the clinker production process, CEMBUREAU has commissioned this study investigating the energy efficiency of the process providing a guideline to evaluate energy performance of a cement production line and the material recovery of alternative fuels utilised in the burning process.

Based on model calculations, the impacts of fuel mix, raw material moisture and bypass rate scenarios on energy demand and energy performance have been examined. Additionally further important aspects regarding co-processing in cement plants have been taken into account. Furthermore, the requirements regarding fuel quality were considered and the actual and potential utilisation of waste heat for alternative fuel preparation and other measures were investigated in three examples.

The study is concluded with considerations on the important role co-processing in the European cement industry can play to achieve a sustainable and future oriented circular economy.

2 Cement production – General description of the clinker production process

Cement clinker is made from a mix of raw materials, namely limestone, chalk and clay, or their natural blend, lime marl. They are extracted from their deposits in general quarries, then crushed, homogenised, ground and finally fed into the cement kiln. These natural materials chemically consist of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3). They are the main constituents of the so-called Portland cement clinker. The following **Figure 2-1** illustrates the production chain starting with the extraction of the raw materials in the quarry via the clinker burning process in the cement kiln until the finished product, cement, leaving the plant by lorry, ship or train.

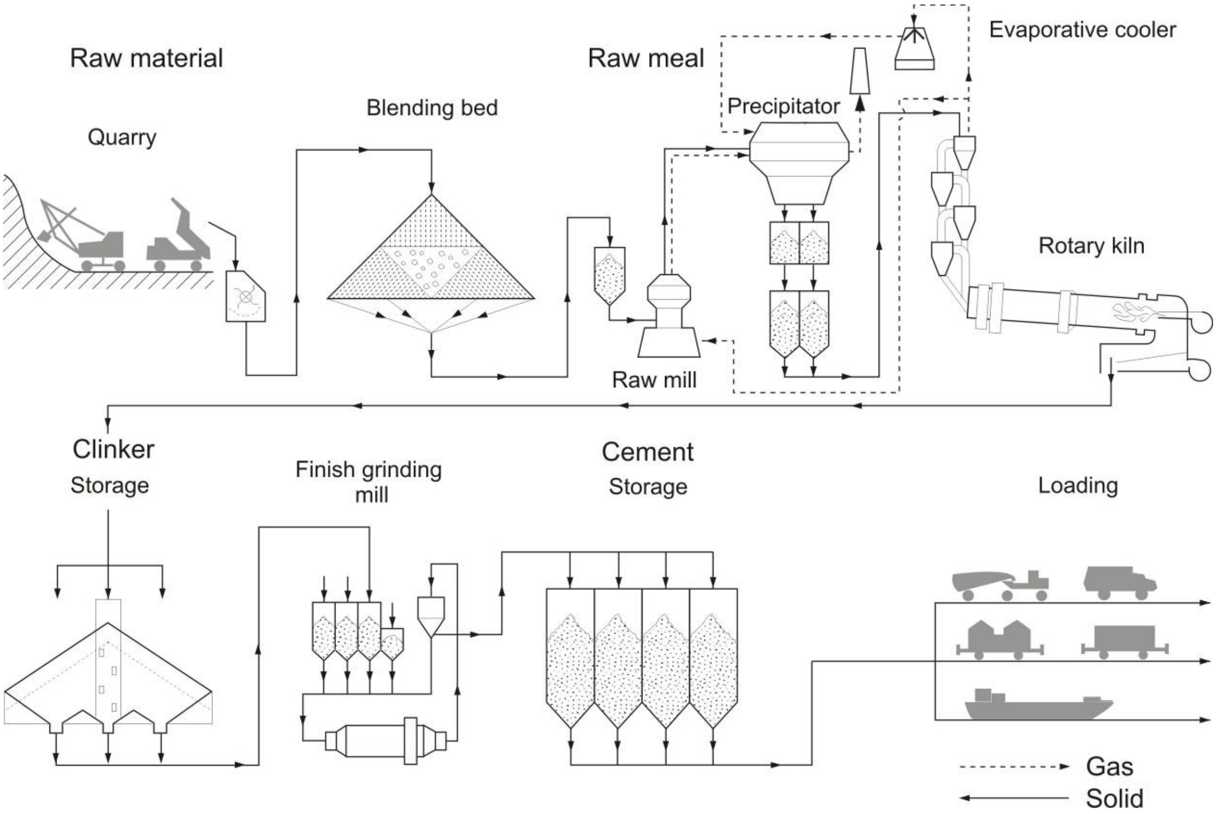


Figure 2-1 Flow sheet of the cement production process

In Europe nearly 100% of the clinker is nowadays burnt in rotary kilns, more than 80% of them are equipped with so-called cyclone preheaters by using the dry process of which more than 60% are equipped with a precalciner. About 10% is produced in grate preheater kilns, the so-called Lepol kilns, and to minor shares in long dry kilns or wet kilns. [CSI 16]

Before passing the kiln, the raw material is fed to this preheater as finely ground meal and preheated to about 750°C by the counter-current flow of the kiln exhaust gas. In the kiln it is heated up to a temperature of more than 1,400°C until it starts sintering. This results in the formation of mineral compounds known as clinker phases. These are certain calcium silicates and calcium aluminates which confer on the cement its characteristic features of hydraulic setting, e.g. hardening when mixed with water.

Cyclone preheater plants comprising precalcining devices are equipped with a so-called calciner (**Figure 2-2**). In rotary kiln plants with calciner and tertiary air duct, part of the heated cooling air is conducted past the rotary kiln to the calciner (tertiary air). It serves as combustion air for fuels supplied in the calciner. The hot meal discharged from the second cyclone stage from the bottom is swept away by the hot gas flowing upward from the rotary kiln and conveyed to the calciner. In this process, the kiln exhaust gas with a temperature of between 900 and 1,100°C in conjunction with the fuel and tertiary air maintain the endothermic calcination reaction with a minimum temperature of approximately 850°C. For this purpose, up to 60% of the thermal input is supplied in the calciner.

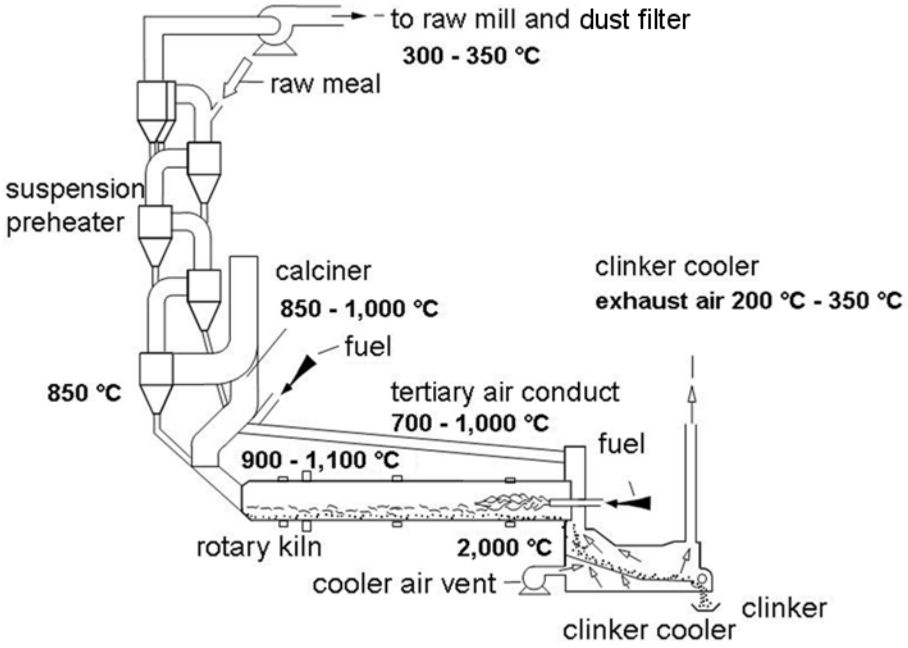


Figure 2-2 Flow sheet of the cement production process

The rotary tube of the kiln is lined with refractory material. Because of the rotation and inclination of the kiln the material is conveyed from the kiln inlet towards the burner, which is installed at the kiln outlet. The residence time of the material through the kiln ranges between 20 and 30 minutes in preheater plants with precalciner and between 30 and 40 minutes in preheater plants without precalciner. From the rotary tube, the clinker is conveyed to the clinker cooler, where it is cooled by air injection. The thermal energy is recuperated in this process, heating up the secondary air (combustion air).

The main firing of the cement kiln with a temperature of up to 2,000°C requires an average net calorific value (NCV) of the fuel mix of at least 18 to 22 GJ/t_{fuel}. In precalciner firings, in which fuel is combusted also low net calorific fuels can be used. Since the net calorific value of most organic materials is comparatively low (10 to 18 GJ/t) these can only be used in the main firing when other fuels with higher net calorific value are used in parallel.

Since energy is reclaimed in the clinker cooler, and the heat of the kiln exhaust gas is also used for drying and heating up the raw material, the clinker burning process claims a high degree of energy efficiency. Finally, the clinker is ground with gypsum and – depending on the type of cement – other cement constituents. While gypsum is essential to control the setting time of wet cement paste, the other constituents (such as blast furnace slag, coal fly ash, natural puzzolan, limestone, etc.) contribute to the performance of cement. Their use strongly depends on regional availability.

3 Guideline to calculate energy performance of cement kilns

For an evaluation of the clinker burning process regarding the utilisation of thermal energy, two main aspects need to be considered and will be described in detail in the following section.

The energy demand of the clinker burning process describes the clinker-specific energy necessary for production (e.g. in kJ/kg$_{\text{clinker}}$). It is influenced by numerous factors such as the plant design (e.g. number of cyclone stages in conjunction with the raw material moisture, plant size, presence of a calciner or the alternative fuel rate).

In contrast to that, thermal energy efficiency (in %) describes the exploitation of energy contained in fuels in relation to the resulting amount of converted and utilised energy. For combustion plants and waste incinerators, this is e.g. characterised by the generated electrical energy or the quantity of heat or steam exported to be used externally for industrial processes or district heating. For production processes such as clinker and cement production, the utilised energy must take into account the thermal energy required for chemical-mineralogical reactions as well as heat recovered internally in drying processes as well as externally for other uses.

3.1 Energy demand of the clinker production process

The cement production process' main target is the production of cement and cement clinker. While the thermal and electrical energy output from power plants or waste incineration facilities may easily be measured, the major share of thermal energy in cement production is required for the endothermic chemical-mineralogical reactions forming cement clinker phases at temperatures of up to 1,450°C with gas temperatures of up to 2,000°C. It amounts to 1,590 to 1,840 kJ/kg$_{\text{clinker}}$ [LOC 06] depending predominantly on the raw material composition and may be calculated for a specific composition of input materials according to the VDZ Code of practice Vt 10 on the Execution and Evaluation of Clinker Kiln Performance Tests [VDZ 11]. It gives thorough details on the balancing procedures of the clinker production process.

Furthermore, kiln exhaust gases are used for the drying of raw materials as an integral part of the production process. Their moisture content may vary significantly depending on the local conditions, such as the deposit itself as well as other environmental factors, such as seasonal rainfall. The drying of raw materials demands an additional energy of typically 200 to 1,000 kJ/kg$_{\text{clinker}}$ with a moisture content ranging from 3% to 15% (see **Figure 3-5**). Therefore, the theoretical minimum energy demand of the clinker production process amounts to 1,790 to 2,840 kJ/kg$_{\text{clinker}}$.

If the preconditions allow it, further waste heat available in kiln exhaust gas, and/or cooler exhaust air is commonly used for the drying of other raw materials for clinker production, fuels as coal and petcoke or cement constituents as blast furnace slag or limestone. Furthermore, some plants utilise waste heat for the drying of alternative fuels. If it is technologically and economically feasible, waste heat may also be used for purposes not immediately related to the cement production process itself. There are examples in the European cement industry using the remaining energy for local or district heating or electricity generation.

Based on the Cement Sustainability Initiative's (CSI) "Getting the numbers right" (GNR) data collection [CSI 16] with the reference year 2014, the CEMBUREAU members' thermal energy demand for the production of grey cement clinker was 3,678 kJ/kg$_{clinker}$ as a weighted average. This includes the production in modern preheater kilns with or without calciner as well as the more energy demanding production in, long dry kilns, wet kilns, semi-wet/semi-dry kilns and shaft kilns with a combined share of about 21% of the total number of kilns. As presented in **Figure 3-1**, the clinker specific energy demand of the CEMBUREAU members varied significantly depending on kiln type as well as for the single installation types. While the highest energy demand is required for the production in wet/shaft kilns with up to 5,800 kJ/kg$_{clinker}$, the lowest energy demand is achieved in preheater kilns with precalciner reaching 3,000 kJ/kg$_{clinker}$.

The actual specific energy demand is strongly dependent on numerous individual factors, such as [based on BAT 13]:

- Size and plant design
    - Number of cyclone stages (influenced by raw material moisture content)
    - Presence of precalciner/tertiary air duct
    - Duration of compound operation of the raw mill
    - Length to diameter ration of the kiln
    - Type of clinker cooler
- Throughput of the kiln
- Moisture content of the fuels
- Raw material properties (such as burnability)
- Specific net calorific value of the fuel mix
- Type and properties of clinker produced
- Homogenising and precise metering of kiln feed material and fuels
- Optimisation of process control including flame cooling
- Bypass rate (in conjunction with the alkali and chlorine input into the system)

The actual annual energy demand of a modern rotary kiln plant under optimal conditions may vary between 3,400 to 3,800 kJ/kg$_{clinker}$ for 3-stage preheater plants and 3,000 to 3,400 kJ/kg$_{clinker}$ for 6-stage preheater plants taking into account the plant utilisation level and fluctuations in the properties of raw materials, fuels, and the process itself. [KLE 06]

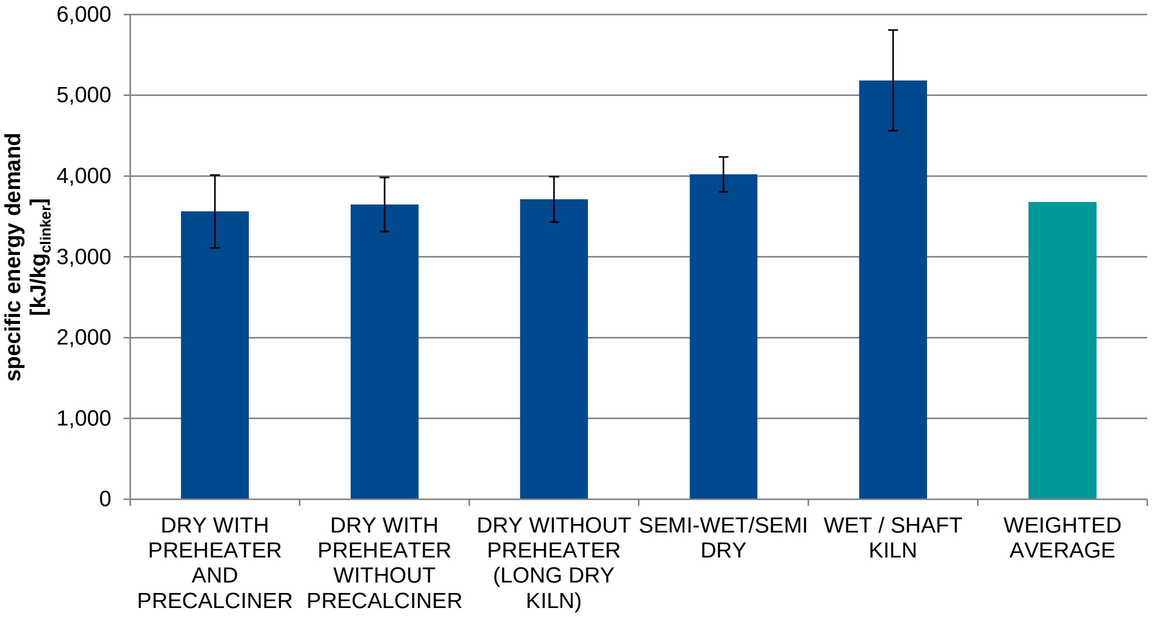


Figure 3-1 Thermal energy demand 2014, CEMBUREAU members, by kiln type [CSI 16]

In contrast to this, the BAT (Best Available Technique) performance level without using alternative fuels for a 3,000 t/d kiln (fired with coal only) mentioned in the European BAT Reference Document (BREF) for the cement industry is 2,900 to 3,300 kJ/kg$_{clinker}$. This has to be seen as a specific energy demand which can in practice be achieved only in short time performance tests in a well-maintained state-of-the-art installation. The European BREF mentions as well, that on a yearly level the energy demand can be 160 to 320 kJ/kg$_{clinker}$ higher because of heating up and shutting down the kiln, kiln stops etc. This results in a BAT range on a yearly level of 3,060 to 3,620 kJ/kg$_{clinker}$ [BAT 13].

The lower the production capacity, the higher are the production specific energy losses. Therefore, a smaller plant with a production capacity of 1,500 t/d exhibits a specific energy demand that is higher by up to 200 kJ/kg$_{clinker}$. A larger plant with a higher production capacity of 5,000 t/d typically exhibits a lower specific energy demand by about 100 kJ/kg$_{clinker}$ [BAT 13].

In [KLE 06] the energy demand of a clinker production process under optimised conditions has been investigated based on process modelling. It has been expanded to include the relation between fuel energy demand and alternative fuel ratio for an exemplary 3,000 t/d plant as presented in **Figure 3-2**. The alternative fuel mix which has been taken as a basis comprises several typical alternative fuels being used in the cement industry. While the range of energy demand for an exemplary kiln using coal only is shown in orange (3,160 to 3,320 kJ/kg$_{clinker}$), the projected range for an increase in alternative fuel use is shown in blue. This modelling, as well as the European BREF document, considers a precalciner kiln with a 5-stage preheater. Furthermore, data from the GNR data base has been taken into account. With an alternative fuel rate of 37.6% for the CEMBUREAU members in 2014, this would lead to an energy demand in the range of 3,290 to 3,450 kJ/kg$_{clinker}$ under optimised conditions as an annual average.

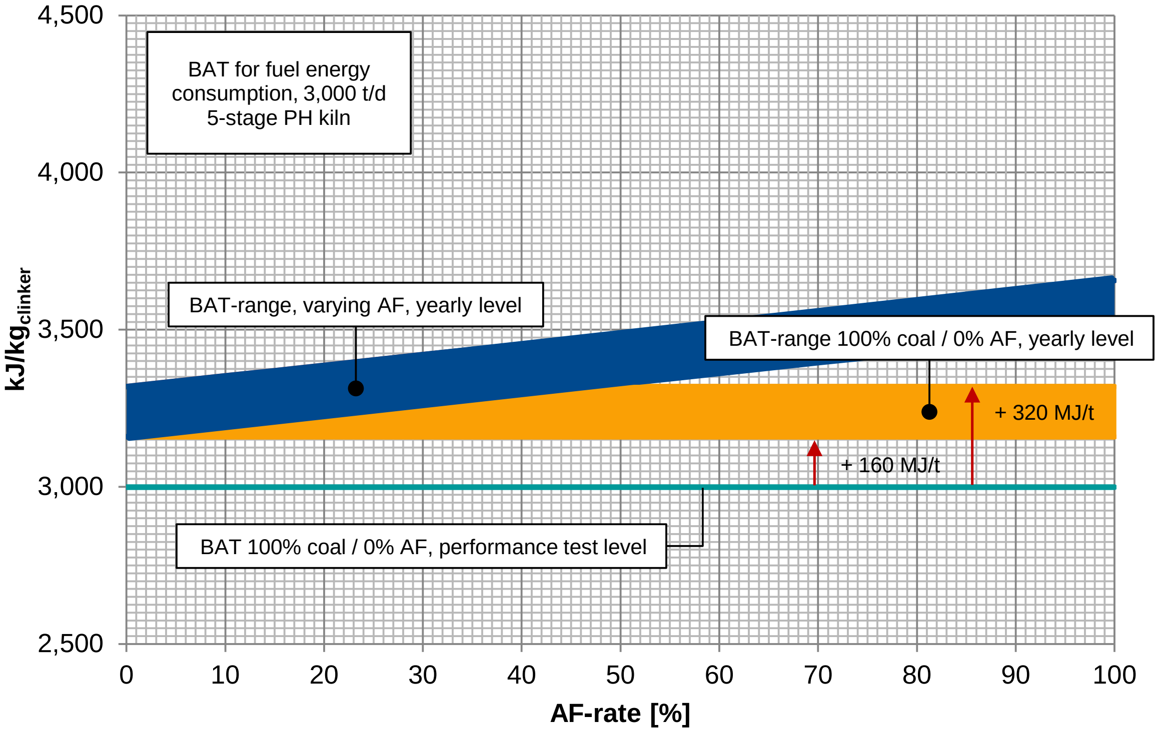


Figure 3-2 BAT related thermal energy demand in relation to AF rate for an 3,000 t/d plant [based on CSI 16 and HOE 13]

In contrast to this, the increase in the use of alternative fuels in the European cement industry (CEMBUREAU members) over the last 15 years has not led to an increase in clinker specific energy demand (**Figure 3-3**). However, experience shows that higher substitution rate may lead to a rising fuel energy demand [KLE 06, HOE 13].

When intending to compare BAT data for annual averages and data from the modelled, optimised kiln with data from the average of the CEMBUREAU members or also an existing installation, it has to be taken into account that BAT data *only considers optimal conditions* and does not take into account individual plant specific characteristics that may result in a notable divergence from the BAT key figures.

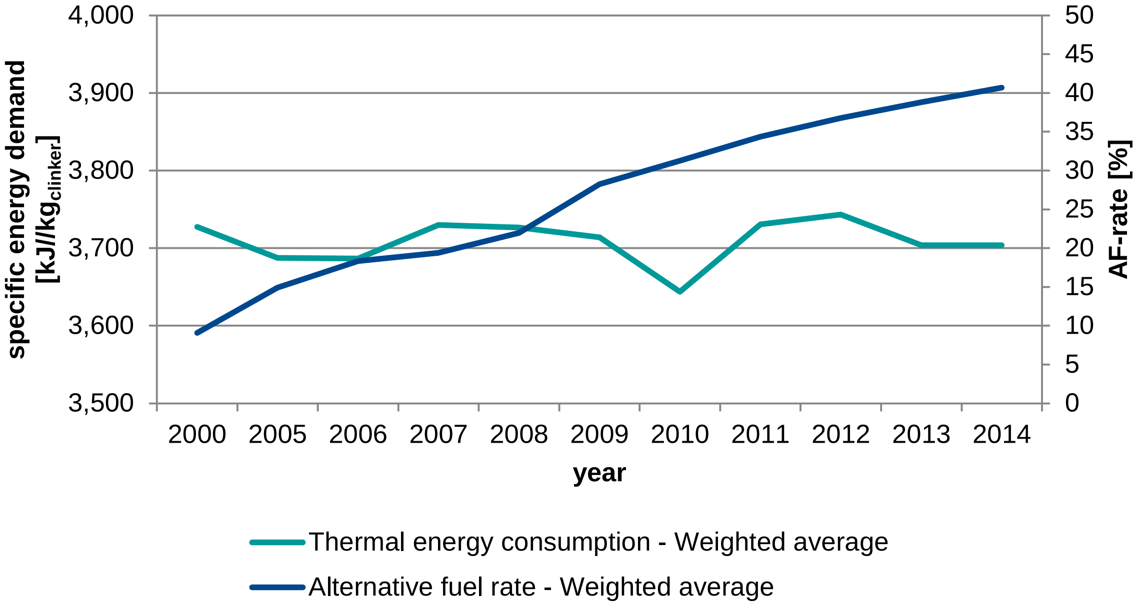


Figure 3-3 Development of clinker-specific energy demand and alternative fuel rate, CEMBUREAU members, 2000–2014, [CSI 16]

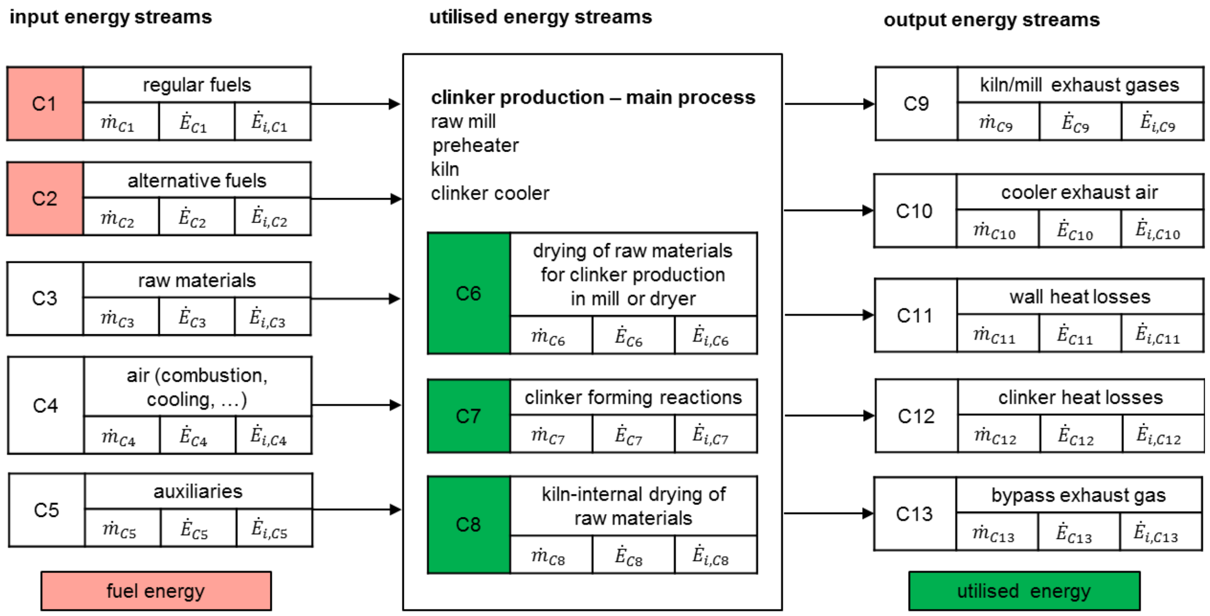
3.2 Energy balance of the clinker production process

Cement plants and kiln production lines in general may vary significantly in their layout and installations where thermal energy is utilised. Therefore the balancing areas presented in the following are simplified to explain the specific characteristics of energy utilisation in the production process, as well as to cover a widest possible range of plants in principle.

The explanation will be split into an energy balance of the clinker production line including the integral process components and steps only, which are the drying of raw materials in a raw mill, the clinker forming reactions. Furthermore, in an extended balancing area, other uses of thermal energy, such as the drying of regular and alternative fuels and the recovery of waste heat from exhaust gases will additionally be taken into consideration.

3.2.1 Energy balance of a clinker production line

In **Figure 3-4** a balancing area for a typical clinker production process is presented consisting of the main process components: kiln line with preheater and cooler and an integrated raw mill. Thermal and chemical energy contained in fuels, raw materials, air and auxiliaries are to be considered in the state as they enter the process. Enthalpies of gases are to be considered immediately after leaving the process (cooler exit, raw mill or kiln exit or bypass exit) before any cooling or other (exhaust gas) treatment is conducted.



with:

$\dot{m}$: Mass stream, $[\dot{m}]$ = t/a

$\dot{E}$: Energy stream, index denotes specific stream, $[\dot{E}]$= GJ/a

$\dot{E}_i$: Energy stream of component i in specific stream denoted by index, $[\dot{E}_i]$ = GJ/a

Figure 3-4 Simplified balancing area for a typical clinker production process

Input energy streams (C1–C5)

The input streams C1–C5 represent all input energy streams to the clinker production line. In addition to energy contained in regular and alternative fuels, this also includes sensible enthalpy in raw materials, air for combustion and cooling and other auxiliary inputs, such as process water for cooling. However, the sensible enthalpy typically makes up less than 5% of the total energy input stream (apart from kiln meal) as the temperature of input materials lies comparatively close to the ambient temperature when entering the process. Therefore they may be neglected for simplification. Apart from that is the chemical energy of raw materials containing a considerable share of organic carbon, (e.g. in clay or specific alternative raw materials). This has to be taken into account in the energy required for the clinker forming reactions (C7).

Utilised energy streams (C6–C8)

Drying of raw materials (C6)

The drying of raw materials is an essential part of the clinker production process and the energy demand depends predominantly on local conditions. Raw materials for clinker production are usually processed in an integrated milling and drying process. The utilisation of kiln exhaust gas for raw material drying by definition is a recovery of waste heat from the kiln's exhaust gas.

An exact energy demand can be calculated from a detailed balance of the mill or dryer, however it may be estimated based on the raw material moisture according to **Equation (1)** [based on MUE 93]. It has been determined empirically from mill balances respecting not only the energy required for the evaporation of surface water, but also the additional amount of energy required for the evaporation of pore water and gore water as compared in **Figure 3-5**.

$$E_{drying} = 0.75\, c_{H_2O}^2 + 55\, c_{H_2O} + 50 \qquad \textbf{(1)}$$

with:

E_{drying}: Clinker-specific drying enthalpy, $[E_{drying}]$ = kJ/kg$_{\text{clinker}}$

c_{H_2O}: Raw material moisture content, $[c_{H_2O}]$ = % by mass

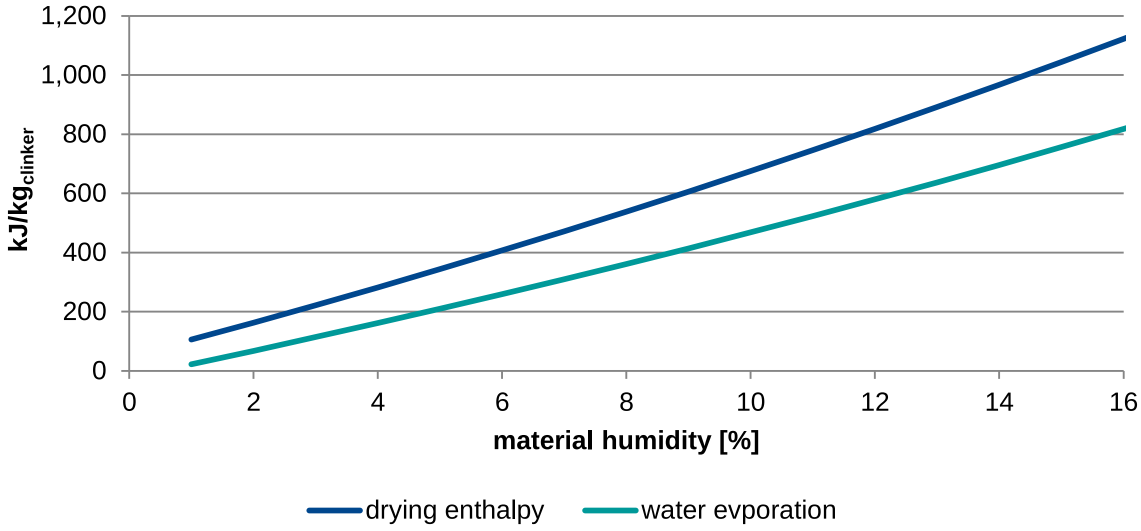


Figure 3-5 Enthalpy required for material drying in a mill or dryer [MUE 93][1]

Clinker forming reactions (C7):

For the production of cement clinker, the dried raw materials need to be heated to a temperature of up to 1,450°C for the chemical-mineralogical reactions to take place. For a given composition of raw materials, the reaction enthalpy may be determined by a series of calculations according to the VDZ Code of practice Vt 10 [VDZ 11], which will not be described in detail at this point. They require extensive chemical and mineralogical analyses of all fuels and raw materials and consider the ash composition of the fuels as well as the content of organic carbon in raw materials. A typical, clinker-specific range required is 1,590 to 1,840 kJ/kg$_{\text{clinker}}$ [LOC 06]. If no detailed analyses are available, a clinker specific reaction enthalpy of 1,750 kJ/kg$_{\text{clinker}}$ may be used as a default value [ROS 87].

Kiln-internal drying of raw materials (C8)

In some cases, raw materials are fed directly to the clinker production process without being dried beforehand in a mill or dryer. The evaporation of water takes place inside the kiln and is an essential process step before the clinker forming reactions may occur. If not considered when calculating the energy required for the clinker forming reactions (C7, above) this utilised energy needs to be accounted for separately. For an evaluation, the kiln-internal drying process can be assumed to have an energy demand of 3,600 kJ/kg of water.

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[1] raw material–clinker ratio: 1.64, remaining moisture content in raw meal: 0.5% by mass

Output streams and losses (C9–C13)

The output energy streams comprise the energy streams leaving the kiln production line i.e. the kiln or mill exhaust gas (depending on the mode of operation), cooler exhaust air, bypass gas, clinker heat losses as well as wall heat losses of the entire kiln line. While the temperature dependent enthalpy in gas streams may be calculated based on a plant's process data according to thermodynamic rules, the wall heat losses of kiln, preheater and cooler can be calculated based on extensive measurements of the surface temperatures of all components in conjunction with the coefficients for radiation and convection. According to [ROS 87], typical wall heat losses lie in a range of < 200 to 600 $kJ/kg_{clinker}$ (for kilns and is influenced by the kiln size and the presence of a tertiary air duct and calciner. As a rule, clinker specific losses are considerably higher in smaller kilns due to the higher clinker specific surface of the kiln line. If no data is available, a default vale of 320 $kJ/kg_{clinker}$ may be assumed.

3.2.2 Extended balancing area for a cement plant including the use of further drying processes and externally recovered heat

The balancing area presented in the previous section covers only kiln and raw mill as the core elements of the clinker production process. For an evaluation of the entire thermal process, the balance boundary of the clinker production process alone needs to be extended to include further integrated fuel and alternative raw material drying processes and other means of waste heat recovery where energy in form of exhaust gas enthalpy is utilised. In **Figure 3-6** the previous consideration is split into the kiln line and the drying of raw materials for clinker production (**C6–C8**). For simplification the various exhaust gas streams from the clinker production process are not allocated explicitly. They are distributed as one stream to the further integrated milling and/or drying processes. Furthermore, material and energy streams are shown as entering the process boundary not explicitly defining their purpose due to the various possible and complex distributions within the actual balancing area of a plant.

Utilised energy streams (C6–C8, P9–P12, P17)

In addition to the utilised energy for drying of raw materials (**C6**), for the clinker forming reactions (**C7**), kiln-internal drying processes (**C8**), exhaust gas streams are in many cases used for the drying of fuels (e.g. in a coal mill), regular and alternative raw materials for clinker and cement production (e.g. blast furnace slag) and less frequently alternative fuels (**P9–P12**). They may be considered according to **Equation (1)**.

Waste heat recovered for external use (**P17**) describes the energy that is being used externally for purposes not immediately connected to the clinker production process itself. As noted, this may be heat utilised for electricity generation or local district heating. Regarding the generation of electricity, a distinction has to be made between the heat provided for electricity generation and the generated electricity itself due to conversion losses. For comparability between the different waste heat uses, the considered energy shall be limited to the utilised heat as the common denominator.

Output streams and losses (P13–P16, P18–P20)

The output energy streams comprise the energy streams leaving the plant, e.g. the stack exhaust gas, cooler exhaust air, bypass gas, clinker heat losses as well as wall heat losses of the entire production line.

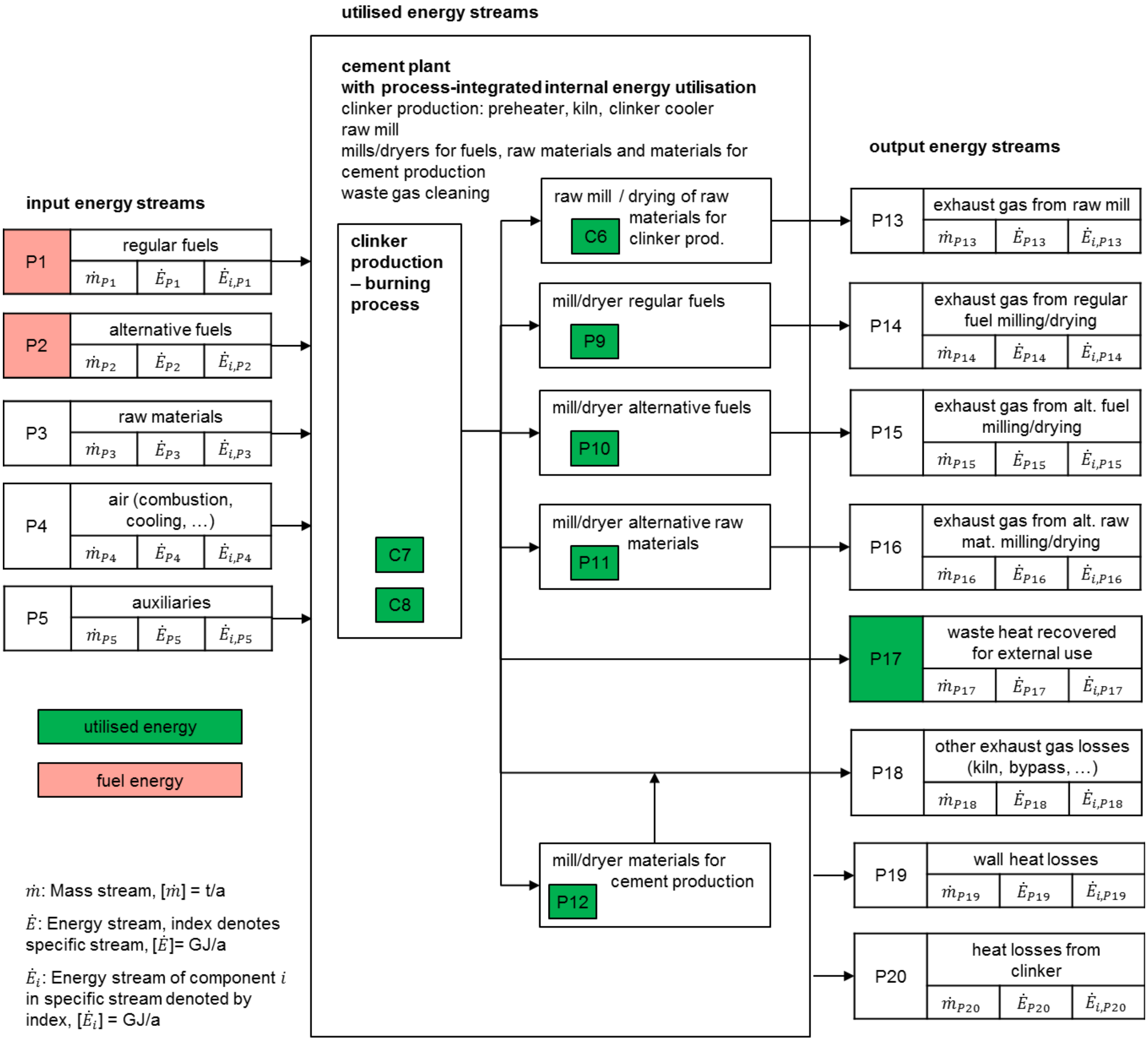

Figure 3-6 Extended balancing area for a typical clinker production line considering the clinker production process as well as the use of kiln exhaust gas for drying processes as well as externally recovered heat utilised outside the balancing area (e.g. for electricity generation or other uses)

3.3 Evaluation of energy performance of the clinker burning process

Based on the presented balances and the thermal energy efficiency, an essential characteristic for a thermal production process such as clinker production needs to be taken into account for an evaluation of the energy performance of the clinker burning process. The main target of the process is the production itself. Therefore the energy required for the clinker forming reactions mandates the process temperature and thus certain energy losses are unavoidable.

Wall heat losses from the kiln are one of the largest specific energy losses from a clinker production line. In the last decades, several attempts have been made to develop a technology to recover this radiation heat. But two essential aspects led to the current status of kiln radiation recovery not being considered state-of-the-art. On the one hand, the radiation heat accrues on a low temperature level so that a conversion would not be reasonable. On the other hand, for a stable and continuous operation it is necessary to constantly observe the kiln’s wall heat to detect and counteract hot spots in a timely manner. This is achieved by using a pyrometer on the blank kiln wall. Since attempts for kiln radiation recovery were not successful, it was tried to add insulation to the kiln wall. But lower temperatures of the steel shell in the heating and transition zone of the kiln led to condensation of alkali salts resulting in considerable damages of refractory and anchoring. [ALL 10]

From a technical point of view, energy recovery is possible from most exhaust gas streams to a high degree. However, two aspects limit the recovery potential. Firstly, a minimum thermal draft in the stack is needed in order to ensure that the exhaust gasses are conveyed and disseminated properly through the atmosphere. Secondly the danger of corrosion due to condensation in filters and stacks needs to be avoided. Therefore, as a rule, exhaust gas enthalpy can only be utilised down to a temperature of 100°C.

Enthalpy of the hot clinker entering the cooler is recovered by preheating the cooler air of which a large share is being used in the process. Clinker leaving the cooler still contains a considerable enthalpy when leaving the process that cannot be recovered even with the most efficient coolers. Cold clinker enthalpy below 100°C therefore may also be considered an unavoidable loss.

The energy performance index as presented in **Equation (2)** takes into account the utilised energy for clinker reactions, drying of raw materials, fuels and mineral components for cement production and further external waste heat recovery as well as mentioned losses, all highlighted in **Figure 3-7**. It enables an evaluation of the energy utilisation with regard to the difference between energy input and unavoidable losses (i.e. the share in energy that actually could be utilised under optimal circumstances) and focuses on the thermal energy not taking into account electrical energy spent for clinker production which typically makes up 3% to 6% of the total energy input for clinker production.

In individual cases where the actual exhaust gas or clinker temperatures lie below 100°C that are considered unavoidable losses, the actual temperatures are to be considered.

$$\varepsilon = \frac{\dot{E}_{C6}+\dot{E}_{C7}+\dot{E}_{C8}+\dot{E}_{P9}+\dot{E}_{P10}+\dot{E}_{P11}+\dot{E}_{P12}+\dot{E}_{P17}}{\dot{E}_{P1}+\dot{E}_{P2}-\dot{E}_{P13,<100°C}-\dot{E}_{P14,<100°C}-\dot{E}_{P15,<100°C}-\dot{E}_{P16,<100°C}-\dot{E}_{P18,<100°C}-\dot{E}_{P19}-\dot{E}_{P20,<100°C}} \tag{2}$$

$$= \frac{\textbf{clinker reactions} + \textbf{raw mat. drying} + \textbf{further integrated drying processes} + \textbf{waste heat recovered externally}}{\textbf{total fuel energy input} - \textbf{exhaust gas losses} < \textbf{100°C} - \textbf{heat losses from clinker} < \textbf{100°C} - \textbf{wall heat losses}}$$

with:

ε: Energy performance index

$\dot{E}$: Energy stream, index denotes the specific stream, $[\dot{E}]$ = GJ/a

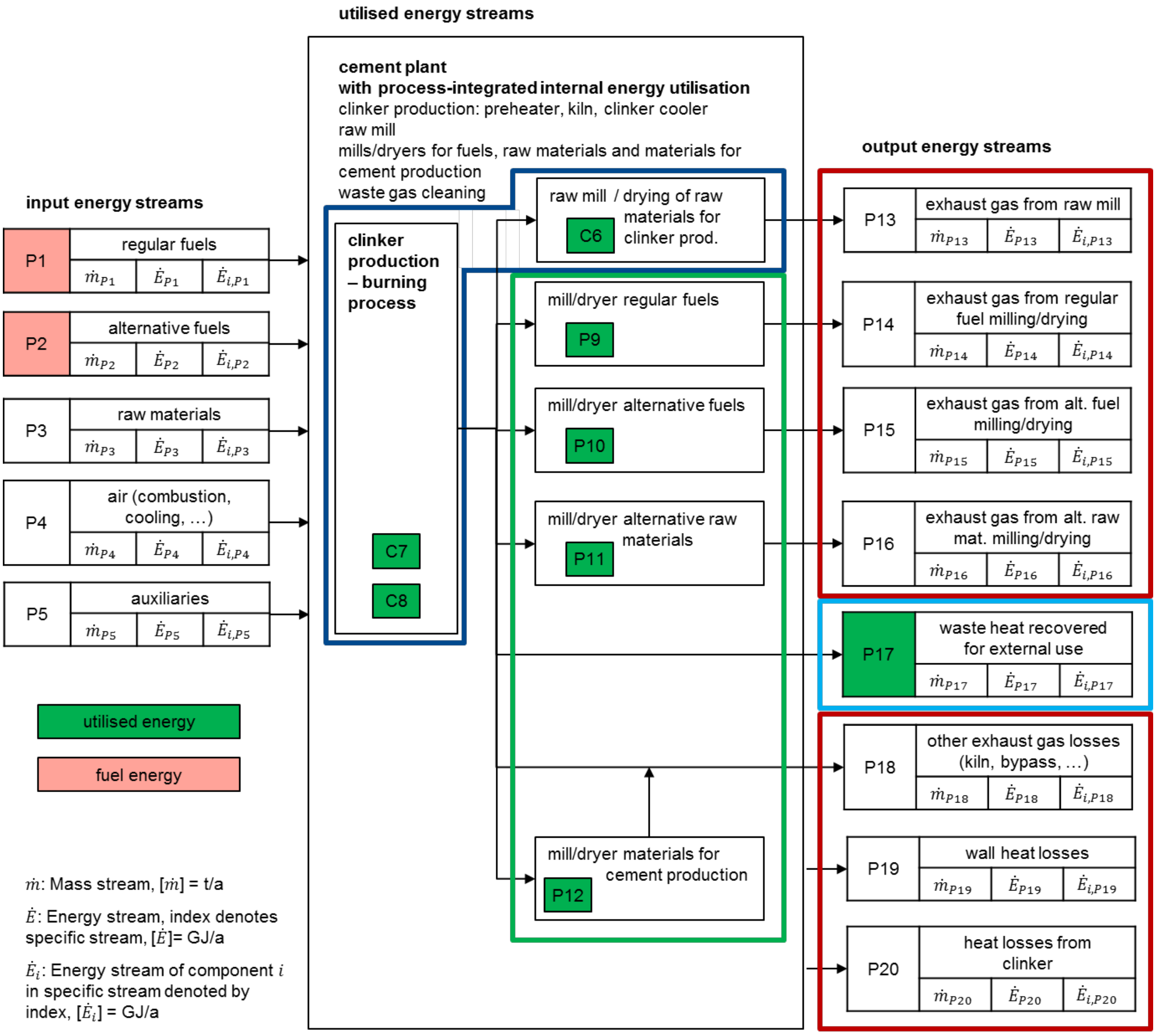

Figure 3-7 Balancing area for a typical cement plant highlighting the utilised energies of the production process, based on **clinker production plus raw material drying**, **further integrated drying processes**, **waste heat recovered externally** and **energy losses, of which for gas streams and clinker only enthalpy below 100°C are considered**

3.4 Average energy performance index for the European clinker production lines (CEMBUREAU members, 2014)

For the CEMBUREAU members, the energy performance index for the cement production process has been calculated to be between 70% and 80% for raw material moisture contents assumed to range from 3% to 7%, **Figure 3-8**. This must be seen an annual industry range according to the previous described extended energy balancing on basis of the GNR 2014 data.

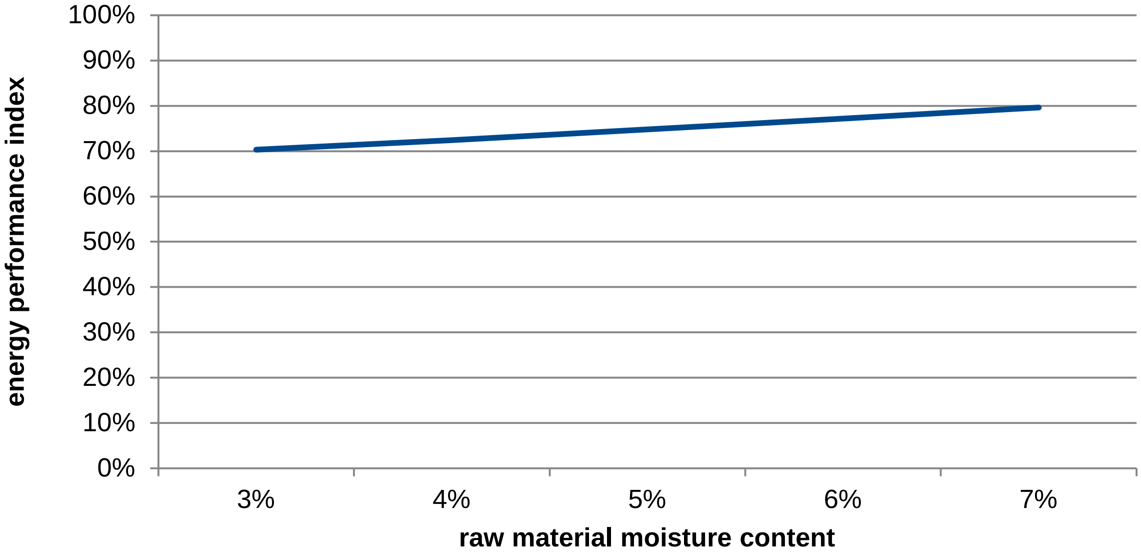

Figure 3-8 Energy performance index in relation to a range of assumed raw material moisture content

Since the GNR data for the CEMBUREAU members is gathered from 216 plants representing about 75% of the industry with an ample range of kiln line designs, assumptions had to be made reflecting typical values for factors determining the energy demand based on [LOC 06] and ECRA experience. The major assumptions are listed in **Table 3-1**.

Table 3-1 Major assumptions and average values for the calculation of energy performance as annual averages

parameter	value	unit
clinker production (CEMBUREAU average)	2,190	t/d
specific energy input (weighted) [CSI 16]	3,684	$kJ/kg_{clinker}$
raw material moisture content	3–7	%
energy for clinker burning reactions	1,750	$kJ/kg_{clinker}$
bypass rate	3	%
specific wall heat losses	320	$kJ/kg_{clinker}$
recovered heat by heat export or electricity generation [based on CSI 16]	28	$kJ/kg_{clinker}$
raw gas temperature (preheater exit)	350	°C
cooler exhaust air temperature	270	°C

parameter	**value**	**unit**
clean gas temperature of kiln and cooler (at stack)	150	°C
specific raw gas volume	1.8	$Nm^3/kg_{clinker}$
specific cooler exhaust air volume	1.0	$Nm^3/kg_{clinker}$
specific clean gas volume (main stack)	2.2	$Nm^3/kg_{clinker}$
specific cooler clean gas volume	1.4	$Nm^3/kg_{clinker}$

4 Comparison of modelled kilns according to raw material moisture content, fuel scenarios and waste incineration plants

4.1 Comparison of fuel scenarios for modelled kilns

The energy demand of the production process regarding BAT kilns under optimised conditions and actually energy demands in various kiln and fuel composition scenarios has been thoroughly investigated in [KLE 06]. To take into account the influence of different fuel scenarios on the energy performance, the considerations have been expanded to include the heat recovery of integrated drying processes. Based on a 3,000 t/d precalciner kiln with a 5-stage preheater, five scenarios have been investigated while the production capacity was set to be constant and three scenarios consider lower and higher raw material moistures with an accordingly varying number of preheater cyclone stages as well as. Furthermore, the influence of bypass rates of 5%, 10% and 15% related to kiln inlet gas volume flow were additionally considered:

- 100% coal, 6% raw material moisture, 5-stage preheater (baseline)
- 100% lignite (10% moisture), 6% raw material moisture, 5-stage preheater
- 40% AF substitution rate, 6% raw material moisture, 5-stage preheater
- 70% AF substitution rate, 6% raw material moisture, 5-stage preheater
- 100% AF substitution rate, 6% raw material moisture, 5-stage preheater
- 100% coal, 3% raw material moisture, 6-stage preheater
- 100% coal, 9% raw material moisture, 4-stage preheater
- 100% coal, 12% raw material moisture, 3-stage preheater
- 100% coal, 6% raw material moisture, 5-stage preheater, 5% by volume bypass from kiln inlet gas stream
- 100% coal, 6% raw material moisture, 5-stage preheater, 10% by volume bypass from kiln inlet gas stream
- 100% coal, 6% raw material moisture, 5-stage preheater, 15% by volume bypass from kiln inlet gas stream

The thermal ratio between kiln firing and calciner firing and the fuel properties are described in **Table 4-2** and **Table 4-3**.

Table 4-2 Overview of fuel scenarios – Modelled thermal ratios of coal and alternative fuels [KLE06]

Scenario / thermal ratio [%]	**100% Coal**	**100% Lignite**	**40% AF**	**70% AF**	**100% AF**
Kiln coal	38	38	38	20	–
Kiln AF	–	–	–	25	57
Calciner coal	62	62	21	10	
Calciner AF	–	–	41	45	43

Table 4-3 Fuels – net calorific values and moisture contents [KLE06]

	Unit	**Coal**	**Lignite**	**AF – kiln**	**AF – calciner**
NCV	kJ/kg	27,000	22,000	20,000	16,000
moisture content	%	0.5	10	12.1	14.4

As described in **section 3.1**, these modelled scenarios consider optimal conditions and do not respect individual plant specific characteristics. Furthermore, means of waste heat recovery exceeding the drying of raw materials for clinker production were not taken into account. Therefore, comparability to the previously presented average energy performance for the CEMBUREAU members is strictly limited. The following evaluation must therefore be seen in the light of potential of energy performance for the different scenarios. In addition to that, it needs to be noted that the individual influencing factors for each scenario often superimpose and therefore, the calculated results cannot simply be added up.

The energy performance including the respective clinker specific energy requirement for the scenarios are presented in **Figure 4-1**, **Figure 4-2** and **Figure 4-3**. A comparison of the energy demand shows, that a switch from dry and high calorific hard coal to lignite (10% moisture content) with a lower net calorific value, results in an increase in specific energy demand that is equal to a scenario where 40% of the thermal input is substituted by alternative fuels. This means, that a substitution by alternative fuels does not necessarily imply a rise in specific energy consumption and a lower energy performance. Both depend on the characteristics of the original regular fuel and the fuel it is replaced by (regular or alternative). Due to differing burnout behaviour and fuel specific combustion gas volumes, the kiln line's raw gas volume and temperature increase with a replacement of coal by lignite as well as by certain alternative fuels. Therefore, the available raw gas enthalpy increases accordingly as shown in **Table 4-4**.

Table 4-4 Influence of fuel use on raw gas temperature, volume flow, and enthalpy [KLE06]

	unit	**100% coal**	**100% lignite**	**40% AF**	**70% AF**	**100% AF**
raw gas temperature	°C	314	340	350	380	409
raw gas volume flow	m^3/h (stp, dry)	153,384	166,378	163,980	176,160	191,477
raw gas enthalpy	$kJ/kg_{clinker}$	660	818	814	967	1,143

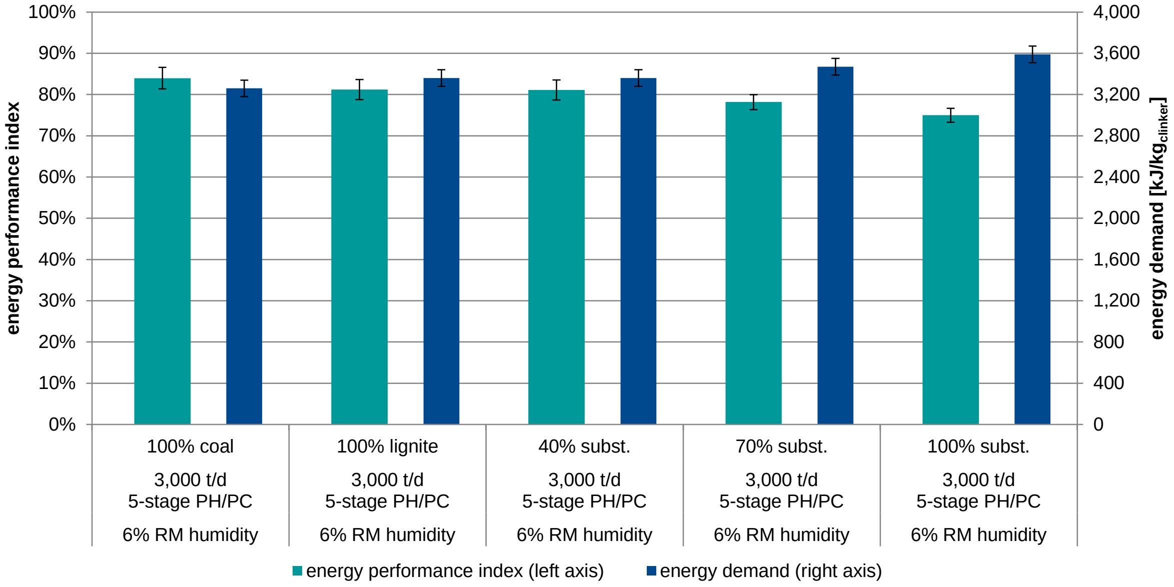

Figure 4-1 Comparison of energy performance index and energy demand for different fuel scenarios [based on KLE 06]

As a result, the energy performance index of the process declines moderately from 83% in the baseline scenario with a substitution by lignite or an increasing alternative fuel rate to 75%. I.e. although the total energy demand rises, this provides a considerable potential for utilisation of further waste heat recovery (drying of alternative fuels, electricity generation, …).

A comparison of the different raw material moisture scenarios with an accordingly different number of cyclone stages in **Figure 4-2** illustrates that higher raw material moistures imply a significantly higher energy demand, but also significantly higher energy performance since a larger share of the input energy is utilised for the drying of raw materials. However, this also limits the potential for further waste heat recovery measures.

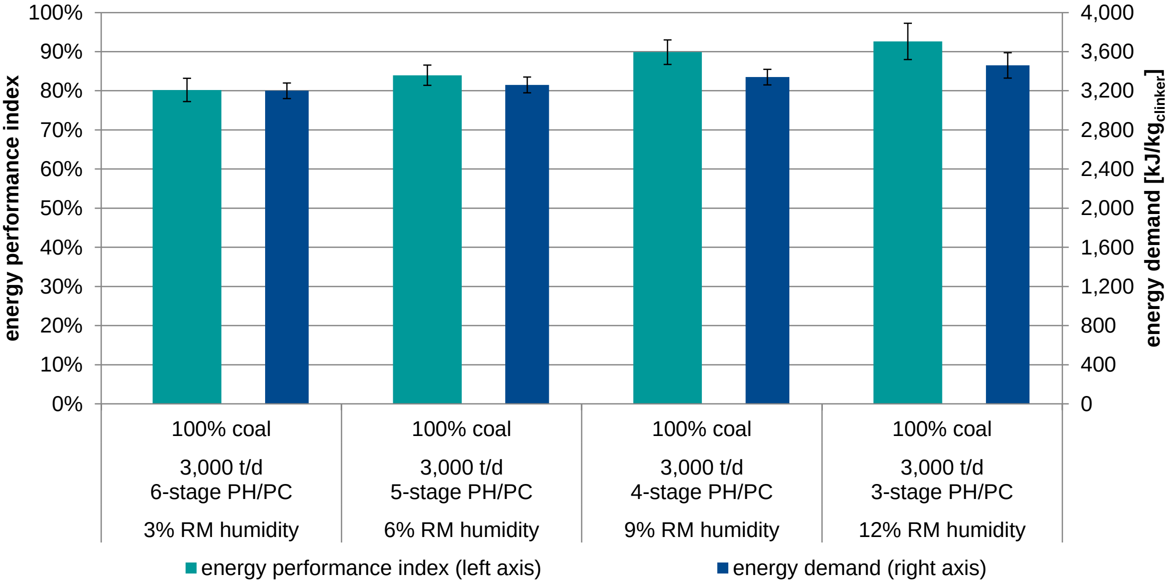

Figure 4-2 Comparison of energy performance index and energy demand for different raw material moisture contents, baseline scenario: 100% coal use [based on KLE 06]

Based on the reference kiln firing coal only, bypass rates of 5%, 10% and 15% related to the kiln inlet gas volume flow are compared and presented in **Figure 4-3**. In relation to the raw gas volume flows (of the BAT precalciner kiln) this corresponds to bypass rates of 1.3%, 2.6% and 3.9% respectively. With an increase in bypass rate, the energy demand increases on the average by about 6 to 12 kJ/kg$_{\text{clinker}}$ per 1% of kiln inlet gas bypass rate in general. Simultaneously, the energy performance index decreases moderately.

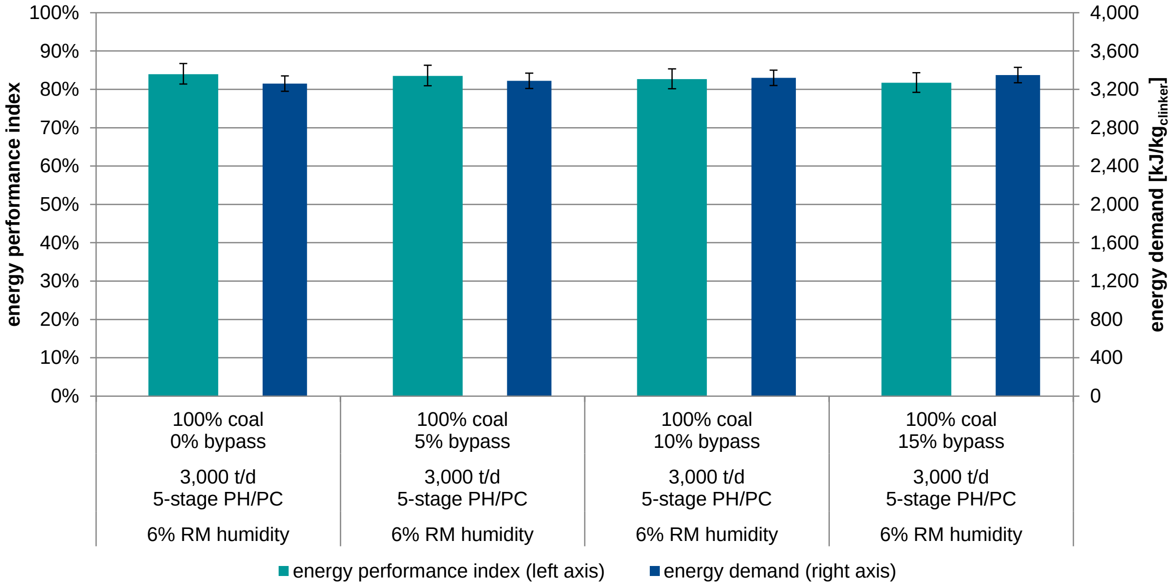

Figure 4-3 Comparison of energy performance index and energy demand for different bypass rates, baseline scenario: 100% coal use [based on KLE 06]

4.2 Energy recovery rate of waste-to-energy plants

The energy recovery rate of waste-to-energy plants as the ratio of recovered energy to total energy spent has been investigated by the Confederation of European Waste to Energy Plants (CEWEP) for the reference years 2007–2010 for 314 Waste to Energy (WtE) plants in Europe (EU27+Switzerland+Norway) [REI 12]. While the combined recovery rate for thermal and electrical energy lies at about 50% as a weighted average, it varies strongly depending on the type of plant. As shown in **Figure 4-4**, the average WtE plant providing heat only, achieves a recovery rate of 77% while a plant designed for electricity generation only achieves a recovery rate of 26%[2]. Plants that generate electricity and provide heat for external use in a combined heat and power process (CHP) achieve en energy recovery rate of 52%. The differences are mainly due to the conversion losses of electrical energy over thermal energy. For 1 MWh of electricity generated, a fuel input of 2.6 MWh is typically required. Accordingly, for 1 MWh of delivered heat, about 1.1 MWh of fuel input is necessary [REI 12].

As presented above, the energy performance of the European clinker production lines lies in the range of 70% to 80%. However, the comparability to the energy recovery rates of the European WtE plants is strictly limited due to the fundamental difference of the processes and their main target. The principal energy utilisation of the clinker production process is mandated predominantly by the energy required for clinker forming reactions and raw material drying and increased by conducting further waste heat recovery, where possible and feasible. In contrast to that, the energy recovery rates of WtE plants is set by the design purpose of the plant (electricity, CHP or heat) determined by the demand for electricity or heat to be provided to consumers in the plants' vicinity.

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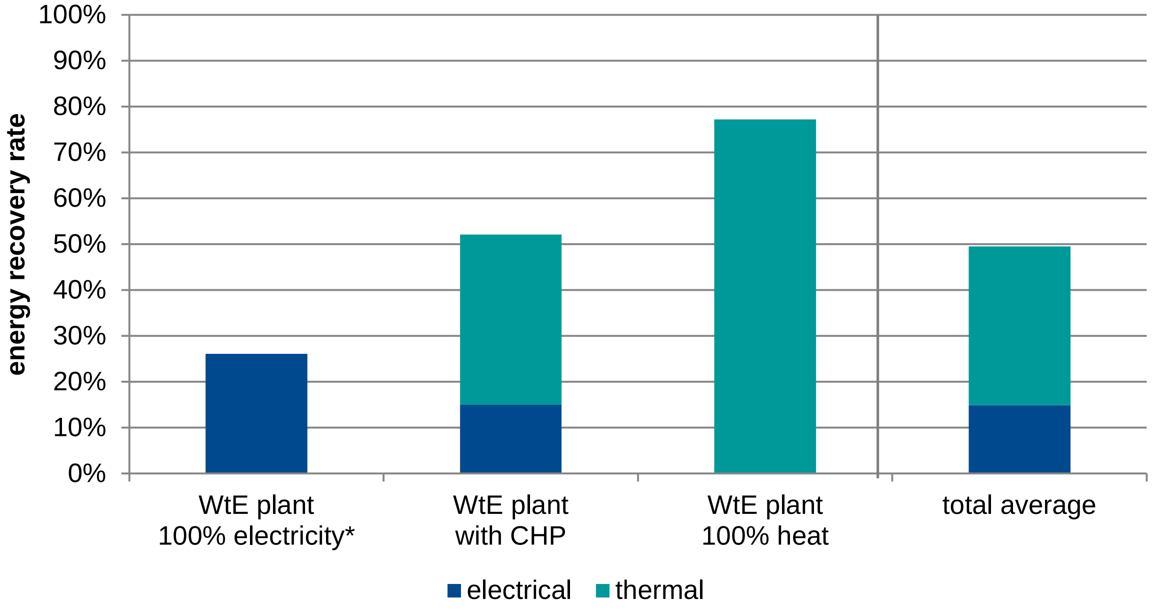
[2] includes 4.5% of heat self used for fuel pre-treatment



* includes 4.5% of heat self-used for fuel pre-treatment

Figure 4-4 Weighted average energy recovery rates as the ratio of recovered energy (thermal and/or electrical) to the total energy input of 314 European WtE plants (EU28+Switzerland+Norway) [REI 12]

5 Characterisation of fuel properties and their usefulness both for energy and material contents and quality criteria for suitable alternative fuels / efforts for pre-treatment

As laid out, the cement production process is very energy intensive. Therefore the use of alternative fuels may reduce the industry's environmental impact as well as energy costs.

The amount and type of alternative fuels that can be used in cement kilns depend on practical, technical and environmental criteria which are in many cases specific for the kilns as such or for the region. For example, the availability of waste is limited, or available wastes cannot be used at all for environmental reasons unless they are pre-treated. This is especially the case for untreated municipal wastes which – besides unfavourable combustion parameters – may have high trace element contents. Furthermore, the plant equipment (e.g. with/without calciner, availability of combustion chamber or gasifier) strongly determines the properties of fuels that can be used.

As a basic rule, alternative fuels (and also alternative raw materials) must give an added calorific and / or material value to the cement kiln. The physical and chemical properties of most alternative fuels differ significantly from those of conventional fuels. While some materials / fuels (such as animal meal) can be easily used by the cement industry, many others can cause technical challenges, such as low net calorific value, high moisture content, or high concentration of chlorine or other trace substances in the wastes under consideration. As a basic rule, the main firing requires an average net calorific value of the fuel mix of at least 18 to 22 GJ/t_{fuel}. In precalciner firings, due to the lower temperatures, also a fuel mix with a lower average net calorific value exceeding 11 to 13 GJ/t_{fuel} may be used. Finally, the properties of the fuel mix must comply with the technical requirements of the respective kiln system, therefore deviations of these values are possible. The following **Table 5-1** shows the typical ranges of the net calorific values for possible alternative fuels.

Table 5-1 Net calorific values for a selection of alternative fuels used in the European cement industry [based on SAV 16]

Fuel	Unit	Net Calorific Value		
		Average	Min.	Max.
Sorting residues	GJ/t	15.0	13.0	18.0
Household and similar wastes	GJ/t	9.0	8.0	10.0
Waste oil (mineral and synthetic)	GJ/t	30.6	27.0	34.2
Waste tyres, waste rubber	GJ/t	29.4	27.2	31.5
Waste solvents	GJ/t	27.5	23.0	32.0
Waste wood	GJ/t	13.4	7.3	19.5
Plastic waste	GJ/t	35.7	19.2	44.3
Paper waste	GJ/t	16.7	9.4	23.9
Textile waste	GJ/t	17.4	13.0	21.8
Animal and mixed food waste	GJ/t	17.0	12.0	25.0
Vegetal wastes	GJ/t	16.0	14.0	18.0
Dried municipal sewage sludge	GJ/t	9.7	3.7	15.7

Co-processing in clinker production offers the necessary parameters for a full burnout of alternative fuels with a minimal environmental impact. The essential process characteristics of current kilns can be summarised as follows [based on BAT 13]:

- maximum gas temperature of approximately 2,000°C (main firing system, flame temperature) in rotary kilns
- gas retention time of about 8 seconds at temperatures above 1,200°C in rotary kilns
- material temperatures of about 1,450°C in the sintering zone of the rotary kiln
- oxidising gas atmosphere in the rotary kiln
- gas retention time in the kiln inlet / calciner firing system of more than 2 seconds at temperatures of gas and solids above 850°C
- uniform burnout conditions for load fluctuations and destruction of organic pollutants due to the high temperatures at sufficiently long retention times
- sorption of gaseous components like HF, HCl, SO_2 on alkaline reactants
- high retention capacity for particle-bound heavy metals
- short retention time of exhaust gases in the temperature range known to lead to de novo synthesis of PCDD/F
- chemical-mineralogical incorporation of non-volatile trace elements into the clinker matrix
- product specific wastes are not generated, some cement plants in Europe of bypass dust
- complete utilisation of fuel ashes as clinker components and hence, co-processing by *simultaneous material recycling and energy recovery*.

Portland cement clinker is made from a raw material mix mainly consisting of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3). For the cement to conform to the quality requirements stipulated, a precisely defined raw material composition must be complied with. Only a small deviation from the ideal composition can be tolerated. **Figure 5-1** shows a ternary diagram for CaO, SiO_2 and $Al_2O_3 + Fe_2O_3$ comprising clinker and ash constituents of different raw materials and fuels. Besides the ingredients of the raw material also those from the fuels finally form clinker. Fuels having a high content of ash are particularly suitable for use in the clinker burning process (see also **section 5.2.1)**. The diagram shows the clinker, the composition of which must be precisely adjusted via the feed materials for the cement to obtain its characteristic hydraulic properties. It can be derived that the lignite ash composition is quite close to that of clinker whereas other ashes do not necessarily meet the required composition. Therefore the amounts and types of alternative fuels have to be chosen carefully in order to assure and maintain a high product quality [VDZ 09].

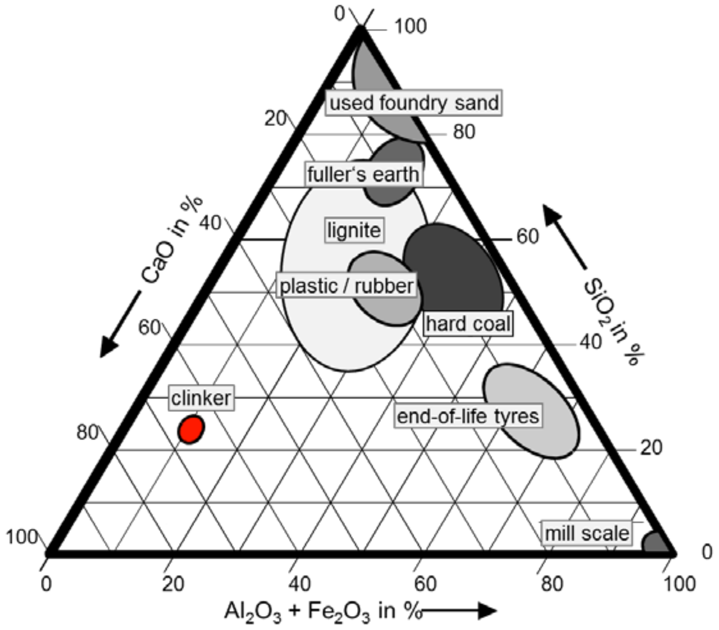


Figure 5-1 Ternary diagram for CaO, SiO_2 and Al_2O_3 + Fe_2O_3 comprising cement clinker and ash constituents of different raw materials and fuels

Independent of its composition some wastes cannot be co-processed at all. This applies for example to nuclear wastes or infectious medical wastes. Untreated mixed municipal wastes require a pre-treatment either externally or on-site. Furthermore, pre-combustion installations have been developed for different kinds of materials that i.e. allow the feeding of bulky material or further increase combustion temperature or retention time (see **section 5.4**).

The following sections give an overview of a selection of alternative fuels used in the cement industry including material characteristics, origin, pre-treatment and special provisions concerning their use in cement kilns.

5.1 Types of alternative fuels

Typical alternative fuels used by the cement industry are

- End-of-life tyres
- Industrial, commercial and municipal solid wastes, construction and demolition waste – RDF and SRF
- Biomass (animal meal, logs, wood chips and residues, recycled wood and paper, agricultural residues like rice husk, sawdust, sewage sludge and biomass crops)
- Plastics, textiles and paper residues
- Waste oils and solvents

Figure 5-2 shows an assortment of typical alternative fuels used in the cement industry. A selection of these will be described in more detail in the following chapters.

Figure 5-2 Assortment of alternative fuels used in the cement industry (source: FLSmidth Pfister GmbH)

5.1.1 Industrial, commercial and municipal solid wastes – RDF and SRF

The term refuse derived fuel (RDF) is not clearly defined, in general refers to a fuel produced by treating municipal solid waste (MSW), commercial and industrial waste (C&IW) or construction and demolition waste (C&DW) by sorting, shredding and drying. While both terms are often used synonymously, solid recovered fuel (SRF) refers to a standardised waste-based fuel in accordance with EN15359 or RAL-GZ 724. **Figure 5-3** shows typical RDF/SRF from packaging and post-consumer plastics, e.g. generated from recycling programs.

Cement plants are in general able to co-process RDF/SRF if the production process' requirements regarding the combustion characteristics are met (net calorific value, moisture content, size, …). Furthermore, especially the inputs of chlorides into the process need to be monitored and controlled. While from an environmental point of view chlorides are usually not relevant in the context of emissions from the clinker burning process (e.g. HCl is neutralised in the alkaline kiln atmosphere), a considerable high input may contribute to an increase in coating formation in the kiln building up over time possibly deteriorating a stable kiln operation. The input of trace elements needs to be monitored and limited with respect to the clinker quality as well as environmental aspect.

For untreated municipal solid wastes, pre-treatment aiming to produce a well-defined waste with limited chlorine content, defined net calorific value and a suitable particle size, size distribution and bulk density is essential for a stable kiln operation.

Figure 5-3 Refuse derived fuel from packaging (source: VDZ)

5.1.2 End-of-life tyres

In 2013, about 3.6 million used tyres accrued in the EU28, Norway, Turkey and Switzerland of which about 75% had reached the end of life. Out of these, about 96% were recovered either by material or energy recovery with similar shares. [ETR 16]

Cement kilns are able to use either whole or shredded tyres as tyre-derived fuel, and offer a simultaneous energy and material recovery of the individual components of the tyres by co-processing. About 91% of the energetically recovered tyres are used in cement kilns. The high net calorific value of the rubber is used to substitute primary fuels and the inert ingredients (mainly iron) substitute part of the raw materials. The inert material, making up usually 25% by mass for car tyres, is entirely recovered being incorporated in the cement clinker. [ETR 16]. Moreover, if the natural raw material does not contain enough iron, the use of tyres helps directly to meet the desired product requirements. Tyres also contain a significant amount of biogenic carbon (about 27% due to the content of natural rubber), thus leading to a direct reduction of fossil fuels related to CO_2. Depending on where they are fed into the kiln, tyres can also deliver a significant contribution to the reduction of nitrogen oxide emissions.

End-of-life tyres are generally stored on the plant area or the quarry in order to minimise transportation paths (**Figure 5-4**). Complete tyres can be fed into the kiln inlet via automatic conveyor belts. However, depending on kiln type and burning conditions, this is not always possible. In these cases they need to be shredded or chipped influencing cost-effectiveness.

Figure 5-4 Storage of end-of-life tyres (source: VDZ)

5.1.3 Sewage sludge

Sewage sludge, as all biomass fuels has in principle a considerable amount of CO_2 reduction potential. Domestic sewage sludge usually contains more than 80% biomass, while the biomass content of industrial sludges strongly depend on the process where they are produced.

For many years, the only solution to dispose of sewage sludge was landfilling or the use as a fertiliser in agriculture. However, sewage sludge may be used as an alternative fuel and raw material in the clinker production process. In 2014, more than 720,000 tonnes of dried sewage sludge have been co-processed in the European cement industry (CEMBUREAU members) making up about 1.4% of the total thermal input [CSI 16].

Several factors determine the quality of sewage sludge. These factors include:

- place of origin (households / commercial and industrial sources)
- quantity and type of surface erosion detritus
- type of sewage plant

In the last few years, stricter legal requirements but also greater understanding on the part of the parties generating waste water have significantly improved the quality of sewage sludge all over Europe, which is particularly evident from the levels of heavy metals. Especially the reduction of mercury levels is of importance with regard to its use in the cement industry. Due to its net calorific value, ash composition and ash content, dried sewage sludge (**Figure 5-5, left**) is highly suitable at the same time for the use as fuel as well as raw material for co-processing in the clinker burning process. The consistency and the net calorific value of sewage sludge depend on the water content. Some sludges have been mechanically dewatered, others have been dried at the sewage plant. Also, some cement plants are equipped to dry dewatered sewage sludge with heat from e.g. the clinker cooler. Each case depends on the site-specific circumstances.

In general, sludge with a moisture content of 10% has got a net calorific value of about 11 GJ/t [SCH 02]. In addition to that, it contains high amounts of phosphorus. As a limited resource it is essential for the metabolism of humans, animals and plants and therefore a main component of plant fertiliser. Regarding phosphorus recovery in the context of sewage sludge as an alternative, current research efforts aim at a treatment of sewage sludge to produce a fuel similar to coal with an optional phosphorus recovery, see **section 5.4.3**.

Mechanically dewatered sewage sludge (**Figure 5-5, right**) may also be considered an alternative raw material in the cement industry giving an additional energy value to the process. Due to the high moisture content and its low net calorific value of up to 5 GJ/t, direct feeding into the kiln system is limited with regard to the minimum average net calorific value of the fuel mix in either main burner or calciner.

Figure 5-5 Left picture: dried sewage sludge pellets (dry matter content > 85%); Right picture: Mechanically dewatered sewage sludge (dry matter content < 30%)

5.2 Quality criteria for alternative fuels

The use of alternative fuels (and also of alternative raw materials) may influence the product (clinker and cement) as well as the process with regard to kiln operation and environmental impact.

- Net calorific value (NCV): The key parameter for the energy provided to the process.
- Moisture content: The overall moisture content (of alternative and conventional fuels and/or raw feed materials) may affect production rate, energy performance and also increase energy consumption.
- Ash content: The chemical composition of the ash needs to be monitored to ensure that the final composition of the raw mix meets the necessary requirements for clinker/cement production.
- Stability of operation (for example, duration and frequency of unplanned shutdowns (CO trips)) and the wastes' state (liquid, solid), preparation (shredded, milled) and homogeneity.
- Alkali, sulphur and chloride content: Excessive inputs of these compounds may lead to build-ups and blockages in the kiln system. Where these cannot be captured in the cement clinker, a bypass system may be required to remove excess compounds from preheater/precalciner kilns.
- Impact on emissions to air

  When alternative fuels are introduced, emissions to air are required to stay below the limits set by the Industrial Emissions Directive (IED). Therefore the alternative fuel needs to be considered regarding the following emission parameters:

  - Organic content: Organic constituents are associated with CO_2 emissions and may result in CO, total organic carbon (TOC) and dioxin/furan emissions if waste is fed through unsuitable points or during unstable operating conditions.
  - Chlorine/sulphur content: Chlorine may in rare cases combine with alkalis to form fine and difficult to control particulate matter. In some cases, chlorine and/or sulphur have combined with ammonia present in the limestone feed. This may produce a visible detached plume of fine particulate with high ammonium salt content.
  - Metals content: The non-volatile behaviour of most heavy metals allows most to pass straight through the kiln system and to be incorporated into the clinker. Introduced volatile metals will partly be recycled internally by evaporation and condensation until equilibrium is reached, with a very small portion being emitted in the exhaust gas. Thallium and mercury and their compounds are highly volatile, as are, to a lesser extent, cadmium, lead, selenium and their compounds. Dust control devices can only capture the particle-bound fraction of heavy metals and their compounds; therefore, emissions of the gaseous species must be controlled.
  - Bypass exhaust gas is typically released with the kiln exhaust gas from a common main stack. In some cases, bypass gas is released from an individual bypass stack. Where an alkali bypass system is installed, appropriate control of the exhaust to atmosphere also needs to be provided on the bypass exhaust, similar to that required for the main exhaust stack.

5.2.1 Recycling index of alternative fuels and added value to the production process

In the clinker production process, the ashes of all used fuels, regular and alternative, become part of the cement clinker and are entirely recovered. To a large extent they contribute to the formation of the clinker phases, thereby giving an added value to the co-processing. Although a continuous fuel quality is most desirable to achieve a smooth kiln operation, fuel properties may vary over time. To evaluate the material recovery of a certain fuel over time or within a time period, the recycling index as the weighted average of a fuel's ash content in a series of fuel batches is defined in **Equation (3)**. [ATIC 14]

$$RI = \frac{\sum c_{ash,i} \times m_i}{\sum m_i} \qquad \textbf{(3)}$$

with:
RI: Recycling Index
$c_{ash,i}$: Ash content of material i, [$c_{ash,i}$] = % by mass
m_i: Mass of material batch i, [m_i] = t

In **Table 5-2** and **Figure 5-6** to **Figure 5-8** the recycling indices i.e. ash contents and chemical compositions of a selection of alternative fuels is presented highlighting the recovery index as well as the added value the fuels give to the clinker production process due to the ashes' high content in calcium, iron, aluminium, silicon and magnesium oxides. Only a minor share is incorporated into the clinker not directly contributing to the formation of clinker phases.

Table 5-2 average ash contents for a selection of alternative fuels

Fuel	RI / av. ash content [%]	standard deviation	number of samples
RDF[1]	12.9	5.2	158
dried sewage sludge[1]	45.0	2.1	11
end-of-life tyres[2]	25	–	–

[1] [ECRA/VDZ data]
[2] [ETR 16]

All fuels, regular and alternative, additionally contribute to the clinker burning process by adding de-carbonated calcium to the process with their ashes. With a raw material to fuels ratio of up to 1:10, each percent (wet basis) of calcium oxide in the fuel ash lowers the specific energy consumption for the clinker formation by up to 2 kJ/kg$_{\text{clinker}}$. This is considered when conducting a kiln balance according to the VDZ Code of Practice Vt 10 [VDZ 11].

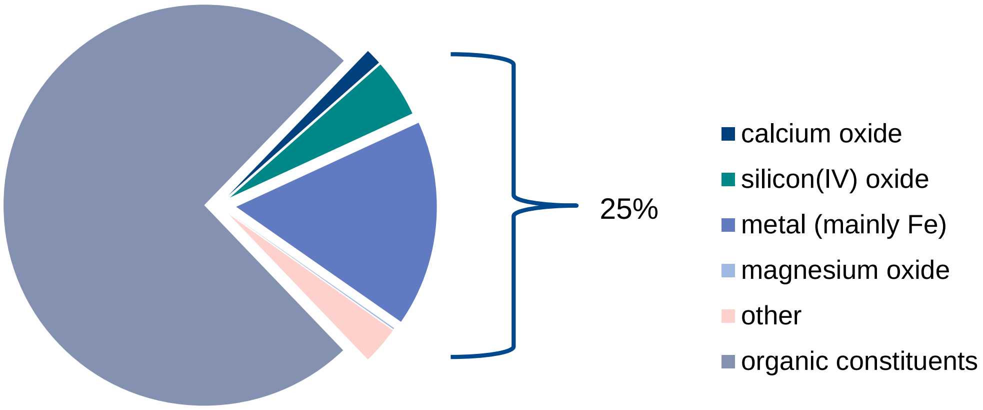


Figure 5-6 composition (dry) of end-of-life tyres [based on ETR 16 and VDZ data]

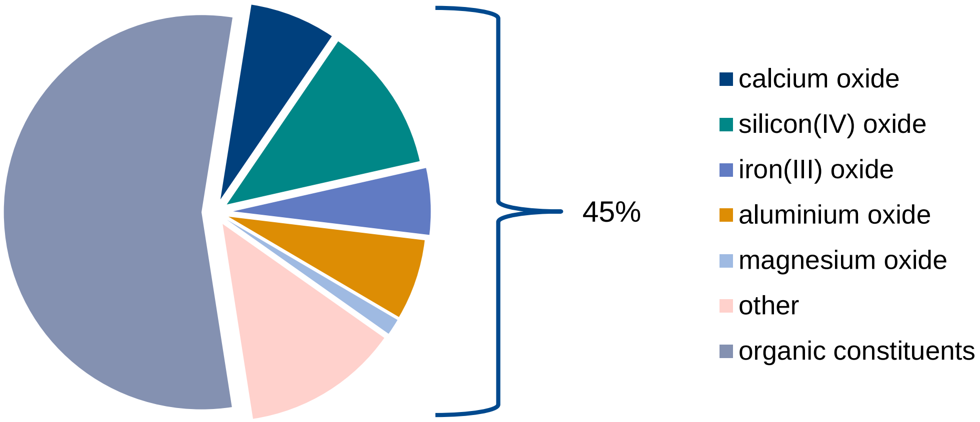


Figure 5-7 composition (dry) of dried sewage sludge [VDZ data]

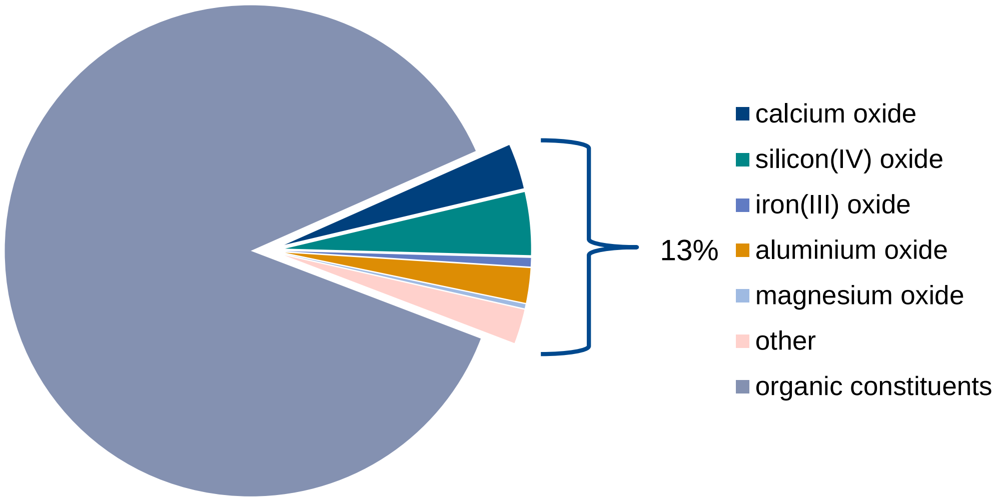


Figure 5-8 composition (dry) of RDF [VDZ data]

5.3 Material efficiency of cement production

The cement production process is highly efficient regarding material efficiency. Fuel ashes are entirely utilised and incorporated in the clinker phases, almost all dust streams are recycled within the clinker burning process or utilised for the production of cement or cementitious products. Only a small portion cannot be used in the process chain. This is typically bypass dust that cannot be utilised as a cement additive due to comparatively high chlorine contents that may negatively affect the cement's properties. This bypass dust, however, in most cases is used for other binding products (e.g. mortar or as a component of stabilisers for roads and in the mining industry)

The clinker burning process goes in conjunction with a weight loss of the raw materials due to the calcination. Therefore it is constructive to conduct an output based evaluation of the material efficiency based on the production volume of cement and the remaining materials not used in the process according to **Equation (4)**.

$$\eta_{material} = \frac{\sum \dot{m}_{cement\ produced}}{\sum \dot{m}_{cement\ produced} + \sum \dot{m}_{remaining\ material}} \qquad \textbf{(4)}$$

with:

$\eta_{material}$: Material efficiency

$\dot{m}_{cement\ produced}$: Amount of cement produced per year, $[\dot{m}_{cement\ produced}]$ = t/a

$\dot{m}_{remaining\ material}$: Amount of remaining material per year, $[\dot{m}_{remaining\ material}]$ = t/a

For a conservative estimate of the material efficiency for the European cement industry, it is assumed, that half of the kiln lines had a bypass system installed and as an average for preheater kilns, 8 g of dust per kg of clinker produced accrued [LOC 06]. Furthermore, half of the dust is assumed to be utilised in cement production directly, e.g. as an additive in the cement mill to adjust specific product properties. The other half of the bypass dust is considered remaining material which is, however, in most cases utilised for other purposes not immediately connected to cement production. This for example may be as a binder in the mining industry.

Under the assumptions made, the material efficiency of the cement production process reaches 99.7%. Therefore, it can be concluded, that a material efficiency of almost 100% is given.

5.4 Efforts for pre-treatment of alternative fuels

For the use of alternative fuels the fuel properties have to stay within a certain range. For example, for the main burner, the average net calorific value of the fuel mix should be above approximately 18 to 22 GJ/t and for use in the calciner its net calorific value should exceed approximately 13 GJ/t. The fuel has to be fine enough so that it burns completely in the gas phase, especially when feeding to the main burner. Alternatively, fuels can also be fed to the kiln inlet. [ECRA 17]

In addition to these and other plant specific boundary conditions, the ability for the use of alternative fuels depends strongly on the availability and infrastructure for the supply of high-quality waste materials and biomass. A recent study conducted by ECOFYS on the status and prospects of co-processing of waste in EU cement plants identified the availability of high quality alternative fuels (e.g. high net calorific value, low chlorine content) a barrier in 11 of the 14 investigated countries. Furthermore and amongst others, the waste market organisation poses a barrier in 6 countries due to either logistical / organisational issues of the market or underdeveloped pre-processing facilities leading to a higher rate of landfilling. [ECO 17]

For plants interested in the increased use of alternative fuels, an on-site treatment of alternative fuels may be an option to increase the suitability for the clinker production process by pre-treatment or pre-combustion, gasification or hydrothermal carbonisation.

5.4.1 Milling and drying

Some alternative materials have high moisture contents and their net calorific values are therefore generally low (e.g. mechanically dewatered sewage sludge: < 5 GJ/t, pulp waste: 6 to 12 GJ/t, municipal solid wastes: 8 to 10 GJ/t). Provided that the kiln is suited for the use, certain amounts of moist and fine fuels such as sewage sludge may be fired directly to the kiln. However, wastes can be dried thermally in the cement plant by using dryers recovering excess heat from the kiln system. If fractions of the fuel are too coarse, mills can be operated to increase the fineness. Some mills are designed for the combined comminution and thermal drying of fuels. By raising the net calorific value and/or the fineness, alternative fuels can be made suitable for the main firing system or the substitution rate can be increased. First installations of dryers and mills for alternative fuels have been reported in the European cement industry, but the technology is still emerging. Belt dryers, drum driers and flash dryers are used for drying sewage sludge, RDF or SRF with clinker cooler exhaust air. Cutting mills and chain mills are used for the comminution of RDF. [ECRA 17]

A positive effect of the drying technology is that moisture can be removed before the fuels are burnt in the kiln, so the kiln exhaust gas volume is reduced, resulting in a lower energy demand for the main ventilation fan. If the kiln fan operates at its full capacity, installing a dryer for the fuel increases the kiln clinker capacity. This positive effect only counts when the moist waste gas of the drying process is not fed back into the kiln system. In other cases additional investments in additional filters or combustion devices have to be installed to clean the dryer waste gas. Additional power consumption for the operation of mills and the dryer has to be taken into account. [ECRA 17]

5.4.2 Pre-combustion and gasification

Pre-combustion or gasification processes allow for more flexibility on fuel quality with regard to homogeneity, net calorific value, moisture content, hazardous contents or sizes. Whereas pre-combustion chambers are operated at excess oxygen, in gasification/pyrolysis processes the fuel is burned in an oxygen-poor atmosphere to generate a lean gas containing CO, H_2 and CH_4. [ECRA 17]

Typical pre-combustion chambers equipped with a burner to support the calciner firing are widely-used. Ignition is enhanced as fuel is combusted in high oxygen atmospheres (21 vol.%) and at higher temperatures (up to 1,200°C). Additional retention time (up to 10 seconds) allows an enhanced burn-out of alternative fuels. Advanced systems even increase the material retention time (up to 45 min) or use stepped combustion to properly combust even different coarse waste materials. The mineral fraction and ashes of the waste and biomass materials are incorporated into the product and thereby recycled (see **section 5.2.1**). Those advanced solutions are commercially available but rarely applied. [ECRA 17]

Using gasification processes a lean gas is provided to the calciner or kiln inlet area, where it is completely oxidised. In this way the energy input can be homogenised leading to a stabilisation of the clinker burning process. Due to the more efficient pyrolysis with regard to the process-integrated drying of the alternative fuels, the gasification technology can counteract the increasing impact of alternative fuel use on the specific energy demand. The gasification can facilitate the use of fuels with net calorific values of e.g. 4.5 to 6.0 GJ/t without pre-treatment, as long as the fuels are appropriate for handling (low fine fraction) and dosing (not sticky) and metallic particles/fractions are removed. Residues from the pyrolysis can either be disposed to disburden certain element cycles or transferred to the raw material preparation/kiln inlet. Recent applications have shown problems with the discharge of hot ashes or unburned particles (e.g. metal wires) or clogging of lean gas tubes to the calciner, which again puts requirements on the fuel quality. In certain applications the introduction of lean gas can generate locally reducing atmospheres leading to additional NO_x reduction. For smaller applications the fuel can be gasified in a fixed bed reactor and above 10 MW in a fluidised bed reactor. Such systems are commercially available but still not widely used. Research projects are also focusing on new gasification routes like plasma gasification. In this approach an electric arc is generated which ignites the alternative fuels. In this way the fuel use could be optimised, but high power demand is related to the generation of the plasma. In any case the resulting lean gas at temperature levels of 800 to 1,000°C offers a net calorific value level of 4 to 6 MJ/m^3 using air as a media and up to 14 MJ/m^3 using steam. The application of plasma gasification in the cement industry has been investigated but is still not proven in demo-scale. [ECRA 17]

5.4.3 Hydrothermal Carbonisation (HTC) and Torrefaction

Hydrothermal Carbonisation (HTC) is a process of carbonisation in aqueous solution, under pressure and increased temperature at about 1.8 MPa and 200°C. It was described in

1913 by Friedrich Bergius and has similarity to the process of geological lignite formation. Nearly any type of biomass can be used as a feedstock, which allows for the use of wet and waste biomass materials, e.g. sewage sludge. After a few hours the HTC char product contains 70% to 90% of the carbon, has similarity to lignite and net calorific values often between 12 and 24 GJ/t depending on the feedstock. About 25% of the energy contained in the biomass feedstock is required for starting the exothermal HTC process and for its electrical energy demand (4,400 MJ thermal and 300 kWh electrical energy per tonne HTC char). The produced char is hydrophobic. Mechanical drying down to 20% residual moisture is therefore very efficient. Thus, the process can offer substantial energy savings compared to traditional thermal drying of biomass fuels. [ECRA 17]

The increased energy density of the HTC product allows for further substitution of fossil fuels in a cement plant by waste-derived biomass fuel. Its inorganic content contributes to the composition of clinker. Currently, the costs of the HTC process limit its economic application to waste fuel sources with significant negative costs, e.g. a gate fee of 50 €/t waste in order to produce HTC char at a cost of 0 €/t. Current research reports are being followed by pilot and industrial scale demonstrations planned in 2016. Further development of the HTC technology and economies of scale may decrease related costs in the future. The potential use of HTC char from sewage sludge as an alternative fuel in the cement industry at a relevant scale will likely require the extraction of phosphorus through a separate acid leaching process and/or the reduction of metal concentrations in the feedstock. At the same time, a potential increase in the chloride or sulphate content of the HTC char might limit its application in the clinker production process. [ECRA 17]

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

5.5 Replacing natural raw materials by de-carbonated alternative raw materials

As laid out, the major share of the thermal energy in the clinker production process is required for the chemical-mineralogical reactions forming the clinker phases. Utilising alternative, already de-carbonated raw materials offers the offers the chance for significant energy savings. Blast furnace slag, lignite ash, concrete crusher sand, carbide sludge, aerated concrete meal or lime residues from the sugar industry are examples of such de-carbonated alternative raw materials. [ECRA 17]

The utilisation of de-carbonated alternative materials is in general influenced or limited by

- their overall composition since they need to be combined with the locally available raw materials and added to the composition of cement clinker. An excess amount of silica, alumina, magnesia or sulphur may therefore hinder a large-scale utilisation of alternative de-carbonated raw materials.

- the content of VOC or trace elements and a variable composition may cause a further restriction in some cases.
- their availability which is is often limited. Further preparation steps, e.g. in the case of concrete crusher sand, may improve the quality of the material but also increase the costs and the environmental efforts for the material supply.

Considering that the local situation may allow only a limited use of alternative de-carbonated raw materials, a use of e.g. granulated blast furnace slag (GBFS) may be realistic up to a share of 15% of the raw meal in some cases. The utilisation of an even higher amount is in principle possible but seems to be unrealistic in any case due to the decreasing availability of GBFS and its rising costs. Moreover, additional effort for the grinding of these materials is needed because of their structure, requiring a higher electrical energy demand. Depending on replacement rate and the share of de-carbonated calcium in the slag’s composition, a use may lead to energy savings in the range of 100 to 400 $kJ/kg_{clinker}$. [ECRA 17]

Additionally, each tonne of alternative raw material may replace 1.15 tonnes of limestone, assuming a share of 50% of de-carbonated calcium in the alternative raw material, and a share of 77.8% of calcium carbonate in the original limestone.

6 Waste heat recovery (WHR) in the cement industry - Case studies for efficient co-processing facilities

Waste heat recovery in the cement industry may be subdivided into the three following groups:

- An extensive share of waste heat is recovered by drying the raw materials for clinker production in an integrated raw mill. This process is essential to the clinker burning process and the required amount of heat depends mainly on the local raw material moisture. Furthermore, if the individual conditions allow it, additional waste is in many cases utilised for the drying of coal in a coal mill and/or raw materials for cement production (e.g. blast furnace slag).
- Depending on the local availability, alternative fuels such as RDF or mechanically dewatered sewage sludge may be dried in a separate mill or drier utilising waste heat. Although numerous plants in Europe use these waste derived fuels, further drying or milling on-site is not widely spread and may be considered an emerging technique (see **section 5.4.1**).
- In conjunction with or as an alternative to the drying of alternative fuels, an external use of waste heat is the third option to recover waste heat from the process. Depending on availability and demand of consumers in the vicinity of a clinker production line, the supply to a local district heating grid or for other industrial processes may be an option to consider if feasible. Otherwise, electricity generation with the conventional steam cycle or with the organic rankine cycle may be an option to consider.

Table 6-1 gives an incomplete overview of European cement plants conducting waste heat recovery divided into the three groups.

In the following three case studies from the European cement industry are presented as examples for means to recover waste heat from the clinker production process by means beyond process-integrated drying of raw materials for clinker and cement production and regular fuels.

The data the studies are based upon was provided by courtesy of the respective cement plant. It has to be noted, that the data are yearly averages and include the effects of start-up and shutdown periods as well as unforeseen stoppages and other factors that may influence operation of the kiln line and waste heat recovery.

Table 6-1 Overview of WHR installations in Europe – electricity generation and external heat supply

WHR by process-integrated drying of raw materials and regular fuels			
The process-integrated drying of raw materials in a raw mill is in principle applied by all clinker production lines. Further recovery of waste heat in coal mills or by drying mineral components for cement production (i.e. blast furnace slag) is common.			
WHR by further process-integrated use – drying of alternative fuels			
Plant	**Company/Group**	**Country**	**Technology**
Alicante	Cemex	Spain	Drying of mechanical dewatered sewage sludge
Allmendingen	Schwenk	Germany	Drying of mechanical dewatered sewage sludge (under construction in 2017)

WHR by further process-integrated use – drying of alternative fuels (continuation)			
Plant	**Company/Group**	**Country**	**Technology**
Bernburg	Schwenk	Germany	Drying of mechanical dewatered sewage sludge
Chełm	Cemex	Poland	Drying of alternative fuels
Čížkovice	LafargeHolcim	Czech Republic	Drying in a belt dryer
Karlstadt	Schwenk	Germany	Drying of mechanical dewatered sewage sludge
Nowiny	Dyckerhoff	Poland	Drying of alternative fuels (flash dryer)
Retznei	LafargeHolcim	Austria	Drying of alternative fuels (flash dryer)
Wietersdorf	Wietersdorfer	Austria	Drying of mechanical dewatered sewage sludge (2014)
WHR by external use (e.g. electricity generation, district heating, …)			
Plant	**Company/Group**	**Country**	**Technology**
Aalborg	Cementir	Denmark	District heating and cooling
Aleșd	LafargeHolcim	Romania	Organic Rankine Cycle (ORC)
Burglengenfeld	HeidelbergCement	Germany	Hot water systems
Fieni	HeidelbergCement	Romania	Organic Rankine Cycle (ORC)
Karlstadt	Schwenk	Germany	Heating of municipal swimming pool
Kirchdorf	Kirchdorfer	Austria	District heating
Lappeenranta	CRH	Finland	District heating
Lengfurt	HeidelbergCement	Germany	Organic Rankine Cycle (ORC)
Parainen	CRH	Finland	District heating
Retznei	LafargeHolcim	Austria	Waste heat recovery
Rohožník	CRH	Slovakia	Organic Rankine Cycle (ORC)
Rohrdorf	Rohrdorfer	Germany	Conventional steam cycle using kiln off-gas and cooler mid-air
Skövde	HeidelbergCement	Sweden	WHR boiler in the kiln off-gas down duct
Slite	HeidelbergCement	Sweden	Conventional steam cycle
Wildegg	CRH	Switzerland	WHR electricity generation
Untervaz	LafargeHolcim	Switzerland	Organic Rankine Cycle (ORC)

6.1.1 Rohrdorfer Zement (Steam turbine)

In 2012 the German Rohrdorfer Zement (Südbayerisches Portlandzementwerk Gebr. Wiesböck & Co. GmbH) has commissioned a plant for electricity generation in a conventional steam cycle utilising waste heat from the cement plant's preheater in combination with the cooler mid-air and the remaining heat of the exhaust gas after a tail-end SCR installation as depicted in **Figure 6-1**.

The kiln's raw gas provides about 220,000 m^3/h (stp, dry) at a temperature of about 430°C. Under normal conditions, less than 30% of this is utilised for the drying of raw materials in a process-integrated raw mill. The largest share of the remaining enthalpy is utilised to generate low-pressure and high-pressure steam for electricity generation in a waste heat boiler. Furthermore, cooler mid-air is utilised for the re-heating of dedusted clean gas upstream an SCR installation for NO_x abatement. The turbine feed water is pre-heated by utilising further recovered heat from the clean gas downstream the SCR installation as well as the cooler mid-air. [UBA 13]

The highly complex installation was incorporated into the plant's existing infrastructure that had grown organically over more than 80 years. Of the investment cost of €32.4 million about €5.4 million was subsidised by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety as part of its Environmental Innovation Programme. [UBA 13]

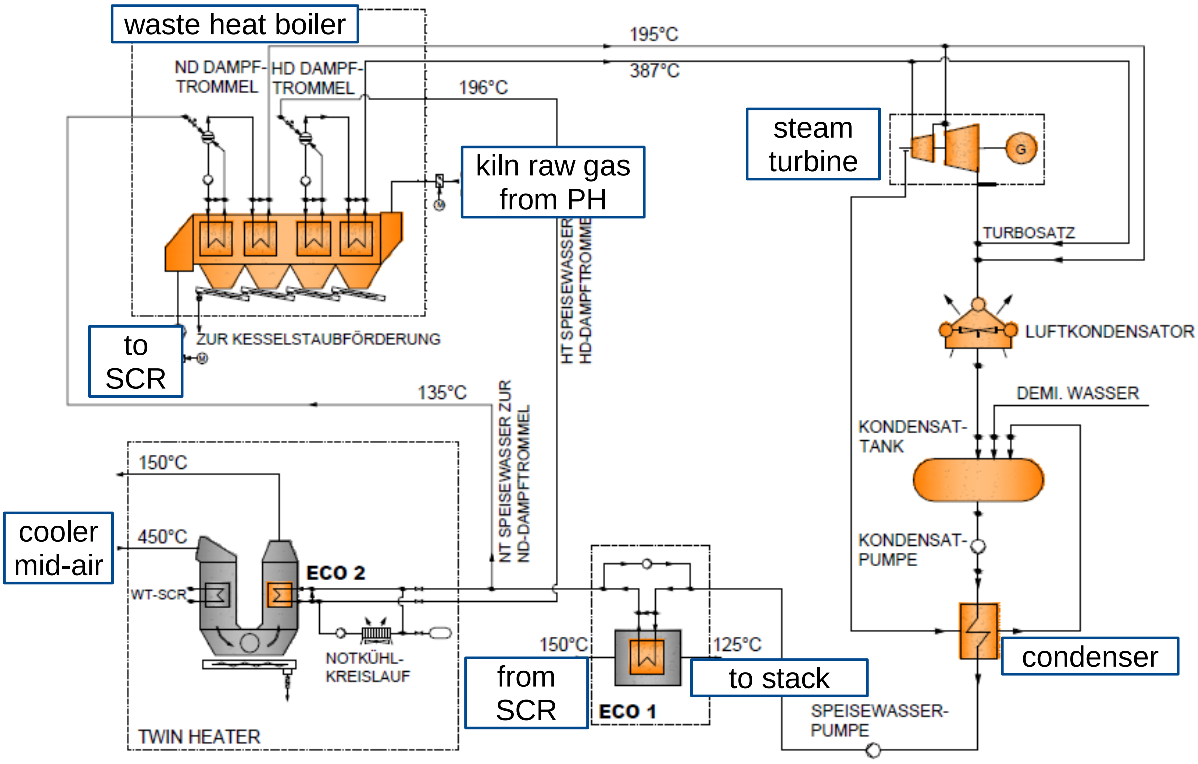


Figure 6-1 Simplified layout of the water-steam-cycle at Rohrdorfer Zement, Germany [UBA 13] with the origin and destination of the gas streams

Based on average data of the reference year 2014 provided, the distribution of waste heat from preheater and cooler has been analysed as shown in **Figure 6-2**. Of the entire waste gas stream from preheater and cooler mid-air, about 28% is utilised for the drying of raw materials for clinker and cement production. An additional small portion is utilised for the operation of the cement mill. About 1% is used for the drying of coal in a coal mill and almost 33% is used for electricity generation. Since the steam turbine is not always operated simultaneously to the kiln production line at full capacity but operation must be adapted to the kiln operation, about 20.1% of the remainder is exhaust gas with a temperature of more than 100°C. About 19% must be considered not usable exhaust gas with a temperature of less than 100°C.

With the electricity generated, Rohrdorfer Zement covered about 27% of its own power demand.

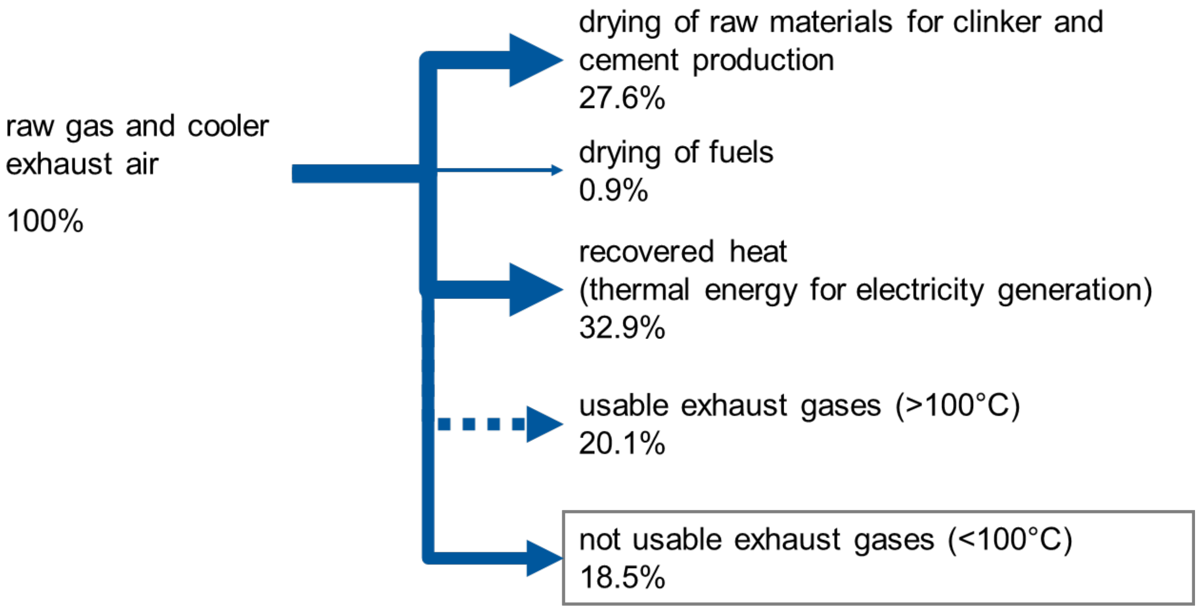


Figure 6-2 Distribution of energy utilisation from the raw gas and cooler exhaust air for the Rohrdorf cement plant, yearly average, data year: 2014

6.1.2 Dyckerhoff Nowiny (flash dryer)

In 2013, the Dyckerhoff Polska plant in Nowiny, Poland using end-of-life tyres and RDF had reached the limit of alternative fuel use at 46% due to the limits of the existing RDF dosing equipment. With the aims to further increase the substitution rate, to increase the net calorific value of the RDF and to stabilise clinker production with a higher clinker quality, the dosing equipment was replaced and a flash dryer was installed.

Utilising about 20,000 m^3/h (stp, dry) of cooler exhaust air with a temperature of 190°C, the moisture content of the RDF is reduced by 3% to 4% and the net calorific value is increased by up to 2 GJ/t as shown in **Figure 6-3** and **Figure 6-4**.

Due to its design, the flash dryer has the additional benefit of acting as a further separator for stone, glass and lumpy RDF particles. On the average, about 20 tonnes of undesired material is collected on a monthly basis lowering damage and wear risk of conveyor pipes and rotary feeders.

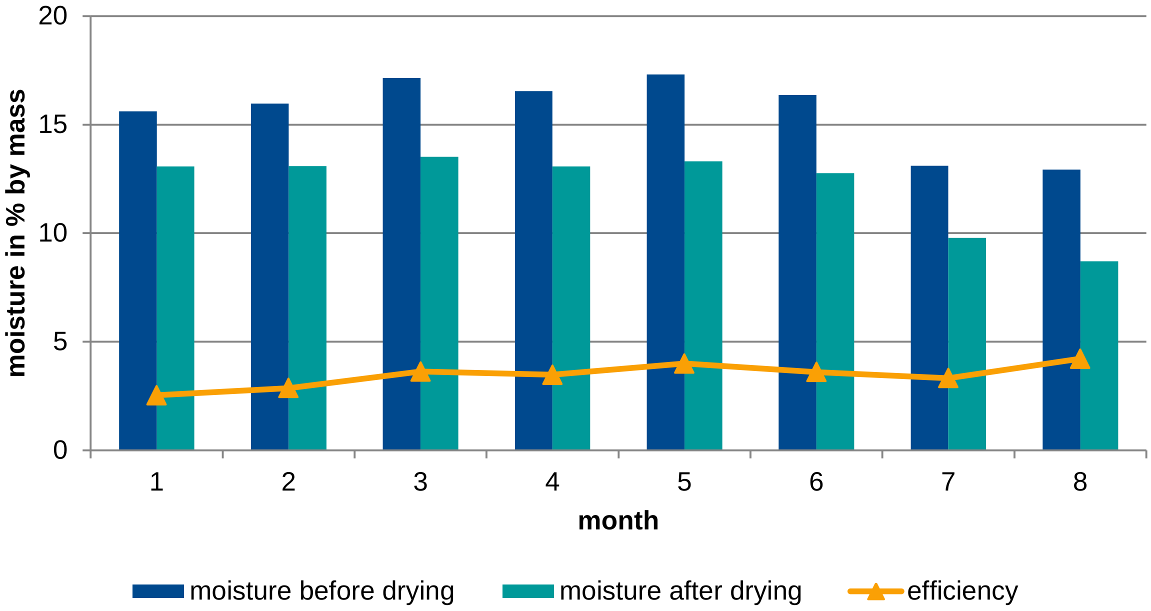


Figure 6-3 RDF moisture content before and after drying over a period of 8 months in the flash dryer at the Nowiny plant, Poland, data year: 2015 [based on RAB 16]

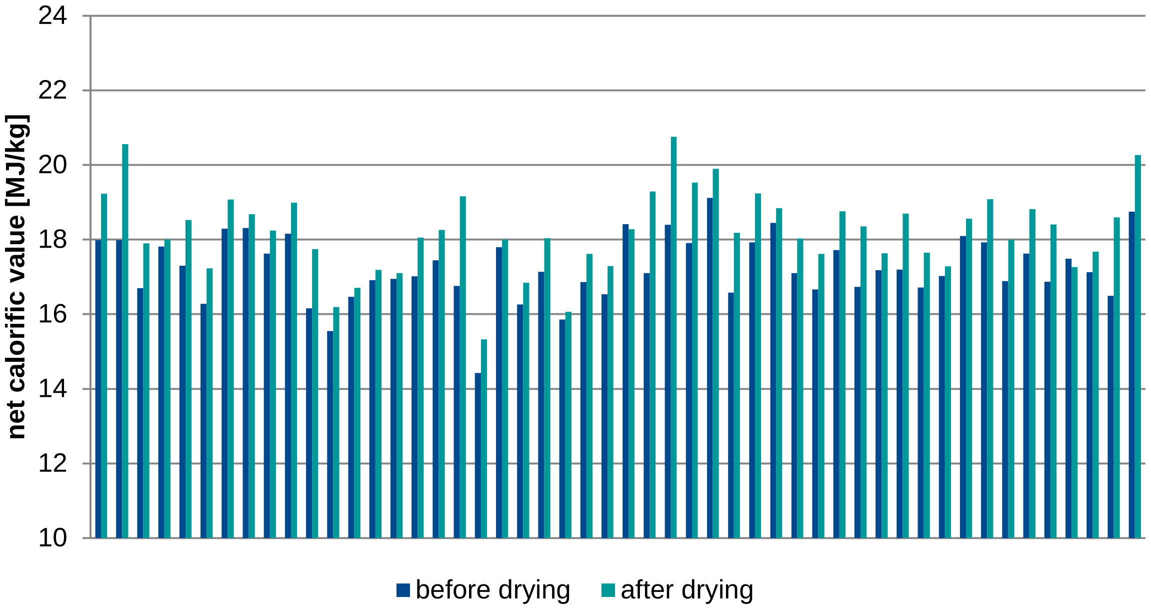


Figure 6-4 Net calorific value of 50 RDF samples dried in the flash drier at the Nowiny plant, Poland, data year: 2015 [based on RAB 16]

Based on data provided of the reference year 2014, the distribution of waste heat from preheater and cooler has been analysed as shown in **Figure 6-5**. Of the entire waste gas stream from preheater, bypass and cooler, about 13% is utilised for the drying of raw materials for clinker and cement production. In the flash dryer, about 1% is utilised for the drying of RDF. While 21% of the remainder is exhaust gas with a temperature of less than 100°C considered not usable, the usable exhaust gas, with a share of 65% provides potential for the application of further waste heat recovery measures.

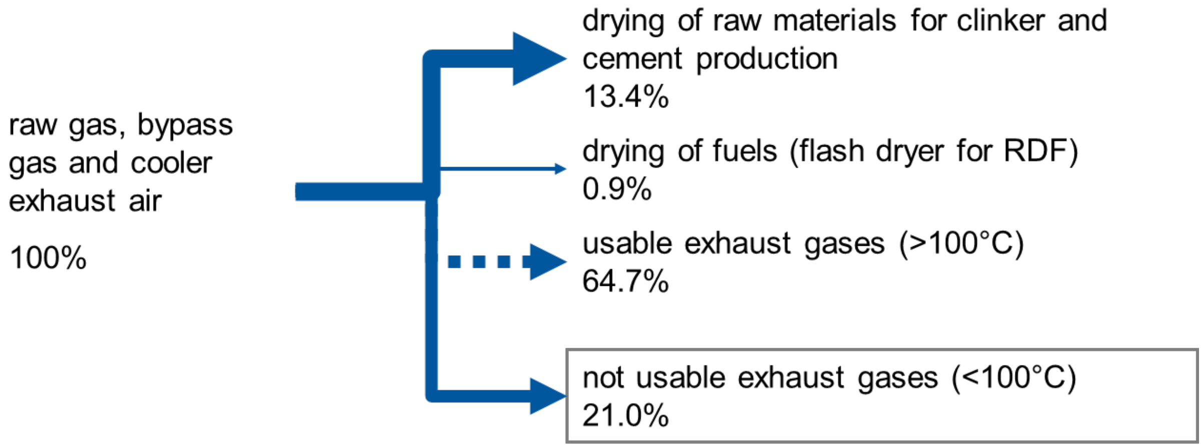


Figure 6-5 Distribution of energy utilisation from the raw gas and cooler exhaust air for the Nowiny cement plant, data year: 2014

6.1.3 Wietersdorfer (sludge drying)

In addition to the drying of raw materials in an integrated raw mill, the Wietersdorf plant of Wietersdrofer & Peggauer Zementwerke, Austria utilised its kiln line exhaust gas and the cooler mid-air for the drying of blast furnace slag for cement production as well as sewage sludge in separate dryers in 2014. From the data provided by the plant, of the total exhaust gas enthalpy, about 23% is utilised for the drying of raw materials for clinker production and further 5% for the drying of blast furnace slag for cement production. Another 8% is utilised in a sludge dryer. About 63% leave the process unused as exhaust gases of which 39% could further be utilised. The remaining enthalpy of 24% with a temperature of less than 100°C is considered unusable.

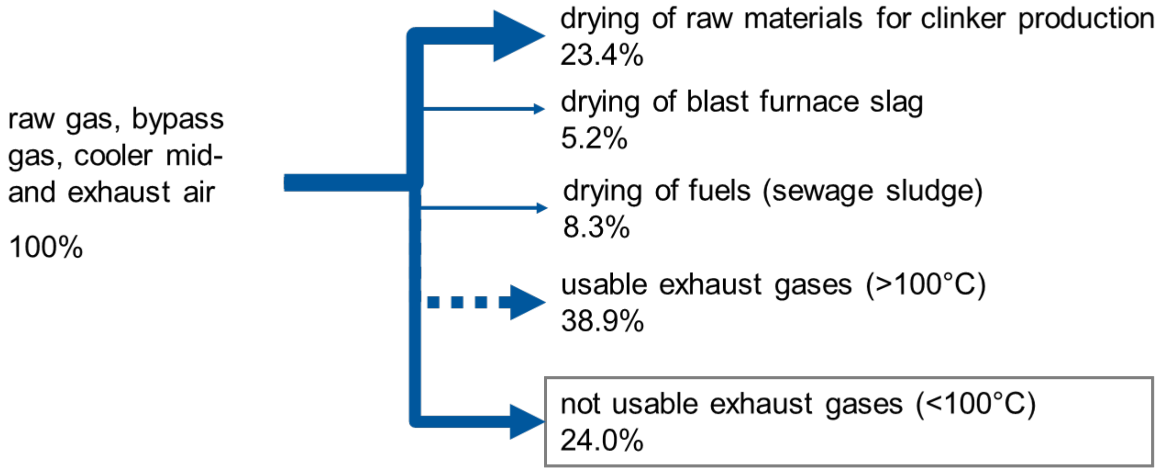


Figure 6-6 Distribution of energy utilisation from the raw gas and cooler exhaust air for the Wietersdorf cement plant, Austria, data year: 2014

By now (2017) the Wietersdorf plant has discontinued the drying of sewage sludge and installed a chain mill for the combined milling and drying of RDF as a pilot installation. About 50% of the total RDF used in the plant is prepared on-site in a combination of two shredders and a chain mill. The RDF is fed to the preparation line in bales and pre shredded to less than 300 mm in diameter. The heavy fraction and iron is separated before a second shredder to a size below 80 mm in diameter. In a stock, the fuel is mixed with RDF from external sources. While fuel for use in the calciner is taken directly from the stock, fuel for the main burner is dried and milled in the subsequent chain mill to a particle size of less than 15 mm. The fine-grained fuel has a high surface and a low moisture content resulting in a better burning behaviour and additionally leads to a higher clinker quality due to its lower content in iron oxide. So far, the heat for drying is provided by the comminution process within the mill, but in the future, the plant is planning to further optimise the drying process by additionally utilising waste heat from the clinker burning process. [NEU 16]

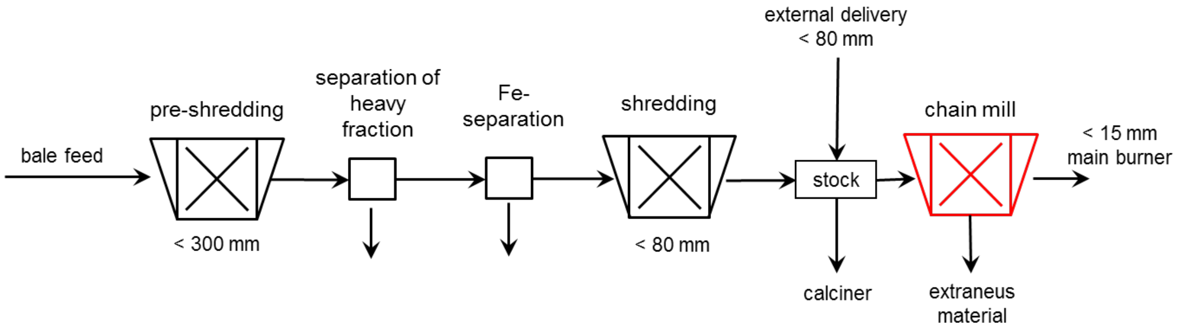


Figure 6-7 Diagram of the on-site preparation of RDF at Wietersdorf plant

7 The role of co-processing in the circular economy

As shown in this study, the clinker production process as such exhibits a high energy performance. The actual figures depend on the specific boundary conditions as well as on the plant layout and the properties of the fuels used (regular and/or alternative).

Due to its process parameters, among them

- gas temperatures of up to 2,000°C,
- material temperatures of about 1,450°C and
- long retention times of more than 8 seconds above 850°C in the main firing,

the process offers the opportunity for using a wide range of alternative materials. As the fuels' inert components, i.e. the mineral constituents of the ashes are entirely incorporated into the cement clinker, the process moreover offers the unique opportunity of a simultaneous energy and material recovery. This specific characteristic is described by the expression of co-processing.

In its recent communication about "The role of waste to energy in the circular economy" [EU 17] the European Commission highlights the importance of co-incineration of waste in power plants and in cement and lime production for the circular economy. In this context, the outstanding role of co-processing as the only technique allowing recycling and energy recovery as a process integrated step in one plant has to be pointed out once again. However, these specific characteristics also demand requirements on the fuel quality.

To start with, the quality of the product cement has to be kept in mind already during the selection of suitable alternative fuels. Moreover, at least if substitution rates above 20% of the overall energy demand are targeted at, the energy content of the fuels must meet certain requirements. The fuel mix for the main firing should exhibit an average net calorific value of above 18 to 22 GJ per tonne. For fuels fired in the calciner, the respective average net calorific value of the mix should exceed 11 to 13 GJ per tonne. Therefore, the use of low net calorific fuels is limited already by the process requirements.

Furthermore, the specific characteristics of the fuels used have an impact on the energy consumption. An increased substitution rate may lead to a moderate increase in the specific energy demand. But this does not give any information of the overall energy performance of the process. In addition to the (minimum) energy required for the chemical-mineralogical clinker forming reactions, waste heat is always recovered by the integrated drying of raw materials in the process. As a matter of fact, plants with high raw material moistures do exhibit a higher energy demand. But as in those cases a higher share of energy is utilised for the drying of the raw material, the energy performance may be even higher. Further heat may be recovered in external drying processes. The application of external waste heat recovery by heat export or electricity generation is a further option for increasing the energy performance of the overall process.

In 2014, 28% of the general municipal solid waste was landfilled in the EU 28 [EUR 17]. However, there is a significant difference in the distribution between the European member states. While in seven member states landfilling rates lie below 10%, 13 countries still landfill more than 50% of their municipal solid waste. This leads the European Commission to the conclusion [EU 17] that there is currently no over-capacity regarding the incineration and co-incineration facilities in the European Union. In this context, it can be concluded that a sufficient potential of suitable waste materials for co-processing exists in the EU and an increased rate of co-processing would contribute to solve the following 3 major challenges [ECO 17]:

- Abate climate change:
  Alternative fuels are one of the main levers for CO_2 reduction in the cement industry. The recent figures of the international energy agency (IEA) show that alternative fuels can contribute to a reduction of 0.75 Gt/a of CO_2 world-wide to greenhouse gas emissions up to 2050 [IEA 15 as cited in ECO 16].
- Improved waste management:
  Co-processing can reduce the volume of waste which is landfilled and additionally efficiently use the energy content of the respective waste. It therefore fits perfectly in the EU waste hierarchy.
- Sustainable implementation of the circular economy:
  The fuel ashes are directly converted into the product cement clinker. By so doing, even the (alternative) fuels deliver a valuable contribution to the product, raw materials are replaced directly.

Examples from several clinker production lines show that substitution rates of 95 % or even higher are feasible from the technical point of view. But such high substitution rates can only be achieved with a comprehensive pre-treatment as well as with a quality surveillance of the alternative fuels.

If these requirements are met, the European cement industry can play an important role in the development of a sustainable and future oriented circular economy. But to reach a high level of the circular economy it has to be pointed out that landfilling of un-pre-treated solid municipal waste should be reduced and in a step by step procedure banned as far as possible. This also means that waste fuels that cannot be used as a resource for co-processing procedures have to be used in dedicated waste incineration facilities and in waste to energy plants.

Finally, a comprehensive and well established circular economy also needs quality criteria for high level recycling.

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