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Master Thesis

Impact of Alternative Fuels on the Energy Efficiency and Process Stability of Cement Plants

written at the

Chair of Thermal Process Technology

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Leoben, 25. April 2018

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I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

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Danksagung

An dieser Stelle möchte ich mich bei meinen Eltern, Dr. Andrea und Dr. Johannes Dock, für die Ermöglichung dieses Studiums bedanken. Meiner Familie und meinen Freunden danke ich für die Unterstützung während meiner Studienzeit in Leoben.

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Abstract:

Due to a highly energy-intensive manufacturing process, enormous consumption of natural resources and substantial contribution to greenhouse gas emissions, the cement industry has a significant impact on society and environment. At the same time, cement companies have to compete in a highly price-driven market. In order to conserve natural resources, fulfil legal requirements and cut down on costs, the Mannersdorf cement plant continues its efforts to increase the use of alternative fuels while decreasing the specific heat consumption for clinker burning and enhancing clinker quality. This Master thesis has the target to assess the thermal energy efficiency of the existing preheater, precalciner, rotary kiln and clinker cooler, analyse process stability issues related to fuel input and reveal potential for improvement. Analyses are carried out based on a kiln audit, online data and an energy balance that was created as part of the audit. The outcome of the subsequent discussion is summarized in a conclusion and optimization strategies are formulated.

Kurzfassung:

Aufgrund des energieintensiven Herstellungsprozesses, des enormen Verbrauchs an Rohstoffen und ihres erheblichen Beitrags zu Treibhausgasemissionen hat die Zementindustrie erhebliche Auswirkungen auf Gesellschaft und Umwelt. Gleichzeitig müssen sich Zementhersteller in einem stark preisgetriebenen Markt behaupten. Um natürliche Ressourcen zu schonen, gesetzliche Auflagen zu erfüllen und Kosten zu sparen, unternimmt das Zementwerk Mannersdorf Anstrengungen, den Einsatz alternativer Brennstoffe zu erhöhen, den spezifischen Wärmeverbrauch für die Klinkerproduktion zu senken und dabei die Klinkerqualität zu verbessern. Ziel dieser Masterarbeit ist es, die thermische Energieeffizienz des vorhandenen Vorwärmers, Kalzinators, Drehrohrofens und Klinkerkühlers zu bewerten, die Prozessstabilität in Bezug auf den Brennstoffeinsatz zu analysieren und Verbesserungspotentiale aufzuzeigen. Als Grundlage für die Analysen dienen ein Ofenaudit, Online-Daten sowie eine im Zuge des Audits erstellte Energiebilanz. Die Ergebnisse der nachfolgenden Diskussion werden in einer Schlussbemerkung zusammengefasst und dienen der Ableitung von Optimierungsstrategien.

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1 Introduction

The introduction of this thesis should encompass the motivation and targets, give an overview over the cement production process and provide a description of the Mannersdorf cement plant, which is the centre of all considerations.

1.1 Motivation and Targets

As shown in Figure 1.1, the worldwide cement production volume is constantly increasing and culminated in 4,198 million tonnes for 2014 [1].

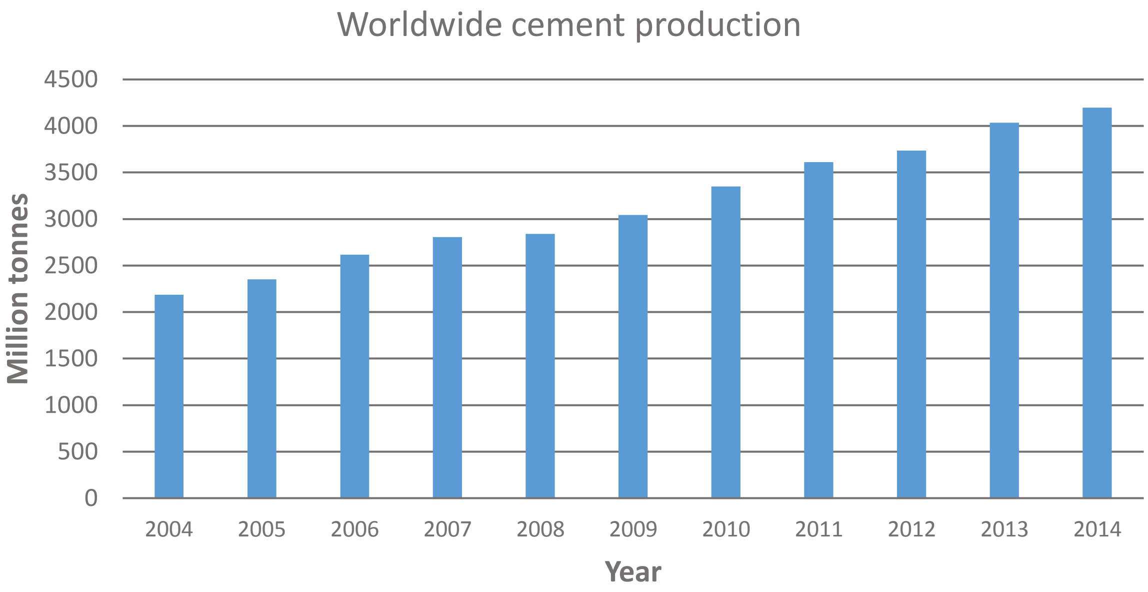

Figure 1.1: Worldwide cement production [1]

Cement is the basis for building materials such as concrete, which is the most consumed substance on earth, except for water [2]. Due to this fact, the cement industry has a significant impact on society and environment, which is not only arising from an enormous consumption of natural resources but also from the emission of CO_2, rising energy costs and the availability of raw materials [2]. Worldwide, the cement industry consumes about 2 % of the global primary energy demand [3] and is accountable for approximately 5 % of all anthropogenic CO_2 emissions [4]. Through the highly energy-intensive calcination and sintering process, most of the energy is used for thermal processing [5]. Due to international efforts to reduce greenhouse gas emissions and a highly competitive market the cement industry is exposed a massive pressure to improve energy efficiency, decrease costs and come up with new technologies for CO_2 abatement [6–9]. At the end of the day, there are two options: Substitute cement as building material, which is doubtful in consideration of Figure 1.1, or develop new ways to handle the mentioned challenges.

This Master thesis has the target to outline the correlation between the use of alternative fuels and the energy efficiency of a cement plant with due regard to the process stability. The starting point is a kiln audit in the plant Mannersdorf, which was conducted in the end of October 2017. With the data gathered during the audit, an energy balance of the preheater, the precalciner, the kiln and the cooler is created according to the standardised procedure of LafargeHolcim. Additional data was provided from the plant's online measurements. As the plant Mannersdorf aims to increase the production volumes, bottlenecks and stability problems are identified and optimisation strategies are formulated. The focus thereby lies on energy efficiency, quality and stability of the kiln, precalciner and preheater.

1.2 Cement Manufacturing Process

The cement manufacturing process is consisting of three steps, which are explained hereafter: raw meal preparation, pyroprocessing and cement grinding. Whilst there are several process routes, 90 % of the European cement production is based on the dry process, which is characterized by the grinding and drying of raw materials to produce a flowable raw meal. Other processes are the semi-dry, the semi-wet and the wet process, in which the raw meal is fed to a grate preheater or kiln in form of pellets or slurry. The disadvantage of wet processes is that the water has to be removed from the raw meal in subsequent production stages. Because of the additional energy that has to be spent to remove the water, these processes are only applied for very moist raw materials today. In Europe, the wet processes are of little importance due to the fact that the more efficient dry process is standard technique [10].

The energy demand for the wet process is about 56 to 66 % higher than for the dry process [11]. As the clinker is manufactured according to the dry process route in Mannersdorf, only the dry process is covered furthermore. Figure 1.2 gives an overview over the manufacturing process in an integrated cement plant without precalciner. The displayed process follows the dry production route.

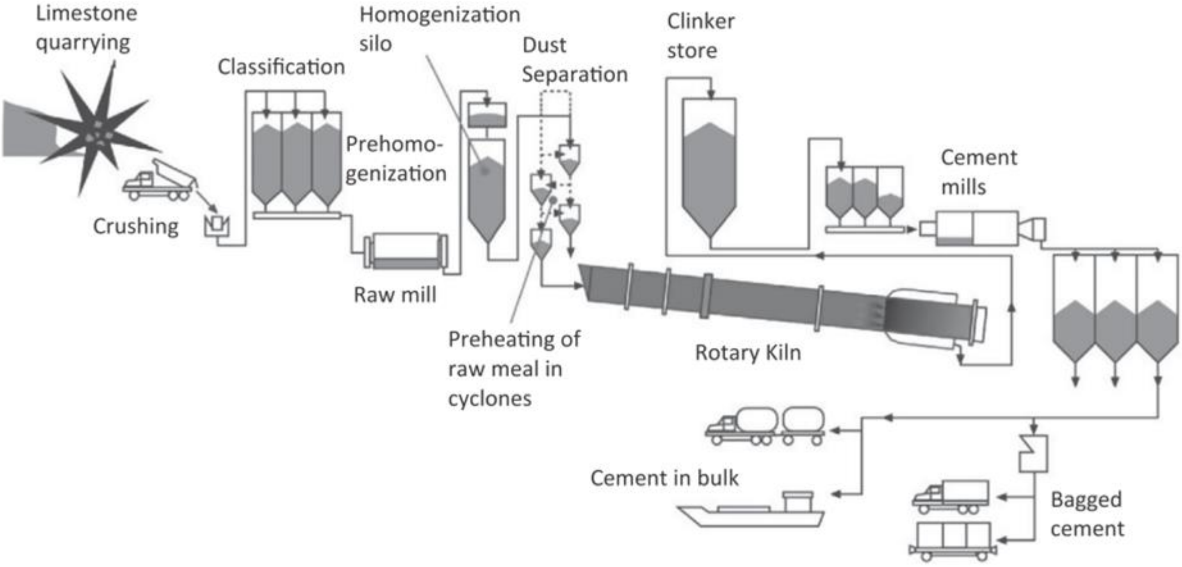

Figure 1.2: Cement manufacturing process [12]

1.2.1 Raw Meal Preparation

Main constituents of Portland cement clinker are calcareous, argillaceous, iron-bearing materials and sand. The required composition can be found in a mixture of limestone or marl, clay, iron ore and sandstone. To cut down on costs and save natural resources, alternative raw materials like crushed bricks or mill scale are used. Coming from the quarry, the raw materials are crushed to a size of about 25 mm and stored. Via conveyor belts and weigh feeders, the materials are fed into the raw mill in the right proportions to achieve the required chemical composition of the raw meal. In the raw mill, which is usually implemented as ball mill or vertical roller mill, the material is further ground and dried to a fine, flowable powder. Hot exhaust gas from the preheater is used to dry the material. Coming from the preheater fan, the filtered exhaust gas passes the raw mill, where it evaporates the moisture in the raw material. To eliminate natural variations in the raw material, the raw meal is fed to blending silos, where it is homogenised, before it is transported to the preheater inlet [2].

1.2.2 Pyroprocessing

As indicated before, most of the thermal energy is required for the pyroprocessing, which includes preheating, decarbonation and sintering of the raw meal as well as cooling the formed clinker. Due to the high heat consumption, this production step offers a corresponding potential for energy efficiency, emission and cost reduction on the one hand but has a major effect on the clinker quality. There are various configurations of kiln systems implemented throughout the industry, but a five-stage suspension preheater and a precalciner as depicted in Figure 1.3 is considered the standard technique for modern cement plants [10].

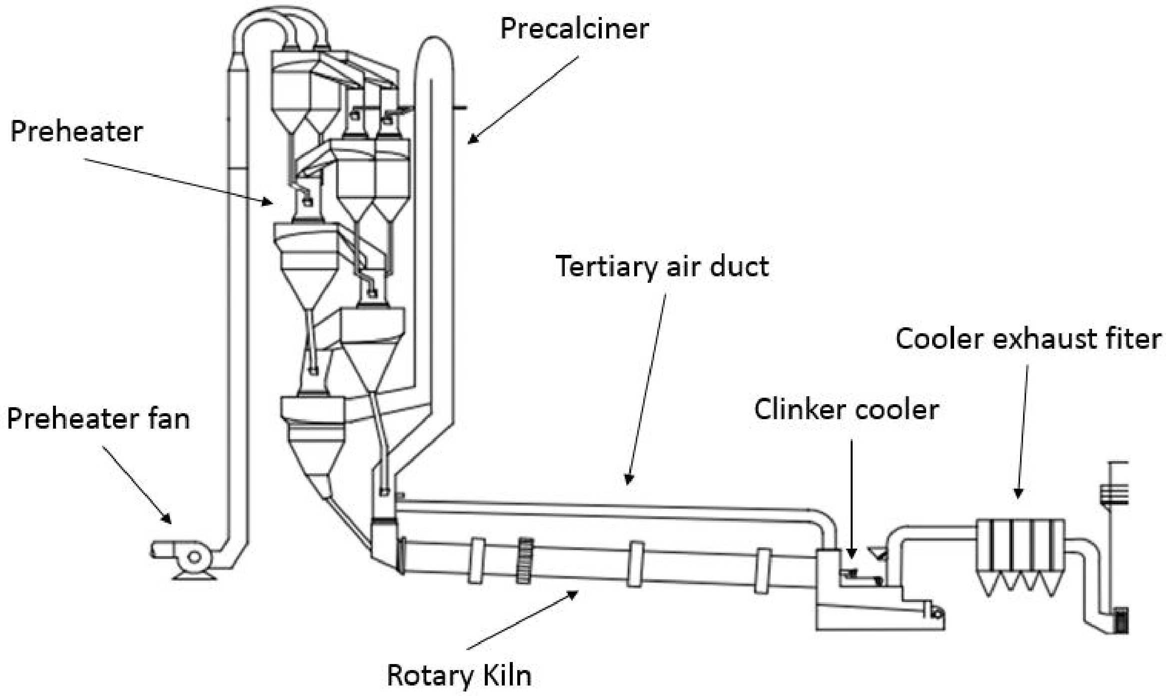

Figure 1.3: State of the art pyroprocessing unit [10]

In the preheater, the raw meal has to pass several cyclone stages and is funnelled by a counter current of hot flue gas from the kiln and precalciner. This suspension allows a highly effective heat exchange between the hot gas and the meal due to a large contact surface. The raw meal is injected into the hot gas stream and separated in the cyclones. This is repeated for each cyclone stage, whereby the meal is preheated until it enters the precalciner. The precalciner is a reactor between the preheater and the rotary kiln, in which secondary combustion takes place. Up to 65 % of the total fuel is burned here together with hot exhaust gas from the kiln and tertiary air from the cooler. The target is to decompose the calcium carbonate to calcium oxide and carbon dioxide, a process, which is referred to as decarbonation or calcination. This reaction consumes a lot of heat. Therefore, gas temperatures of around 900 °C and a reasonable retention time of the raw meal is required according to Figure 1.4 [10].

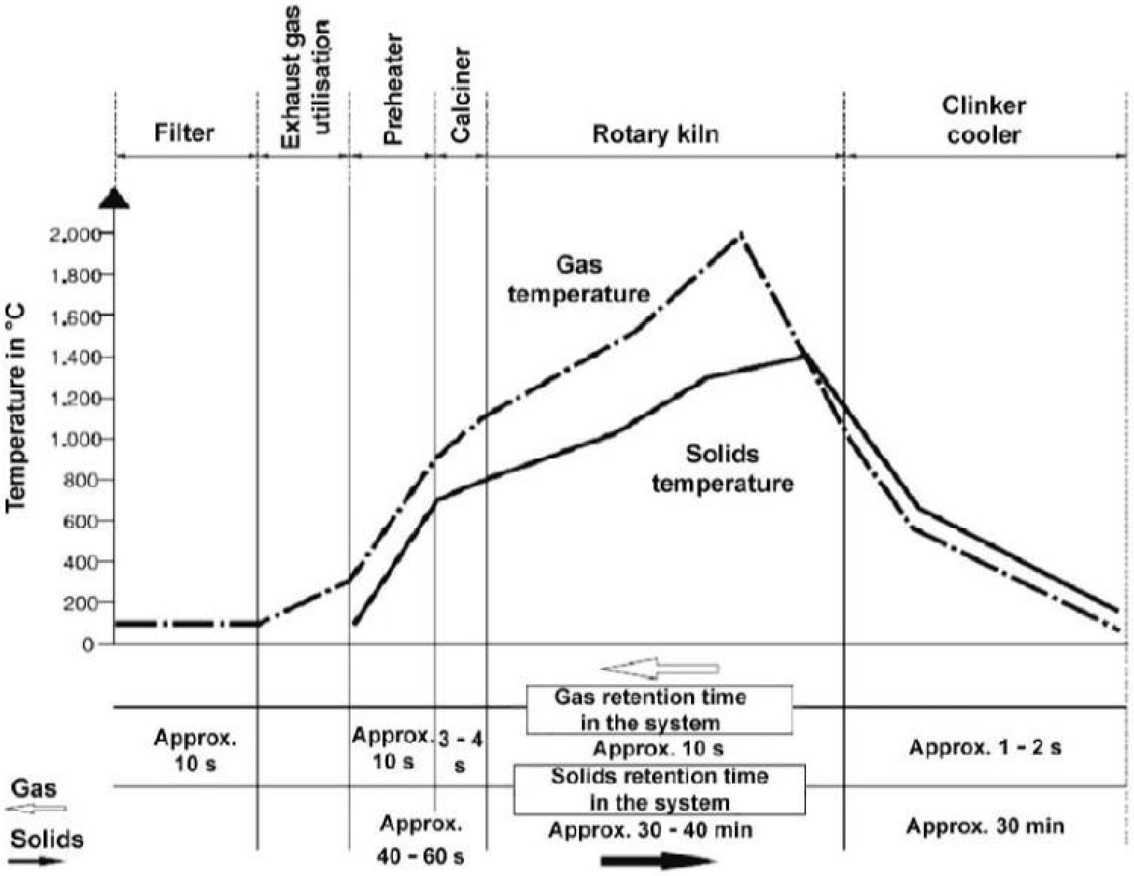

Figure 1.4: Temperatures and retention times for clinker burning reactions [10]

One more cyclone stage separates the hot meal from the gas stream before it is fed into the rotary kiln. A flame temperature of 2000 °C at the main burner is necessary to increase the meal temperature to about 1450°C in the sintering zone, where the reactions to form clinker take place under oxidising conditions. The inclination of 2.5 to 4.5 % and the rotational speed of 0.5 to 5.0 revolutions per minute take care of the material transport in the kiln. Coming from the rotary kiln, the sintered material has to be cooled down and crushed in order to recover as much heat as possible and to make the clinker storable. There are various types of coolers, which fulfil the same target. They fall into two main groups, namely rotary coolers, in which the clinker is cooled by the airflow through a rotating tube and grate coolers, in which the clinker is lying on a travelling or reciprocating grate and cooled by an air current from below [10].

Target of the pyroprocessing is the generation of the four main clinker phases Alite (C_3S in cement chemistry notation), Belite (C_2S), Ferrite (C_4AF) and Aluminate (C_3A), which have the chemical formulae [13]:

- Tricalcium silicate (C_3S): $3\ CaO \cdot SiO_2$
- Dicalcium silicate (C_2S): $2\ CaO \cdot SiO_2$
- Tetracalcium aluminoferrite (C_4AF): $4\ CaO \cdot Al_2O_3 \cdot Fe_2O_3$
- Tricalcium aluminate (C_3A): $3\ CaO \cdot Al_2O_3$

The distribution of clinker phases in the product is dependent on temperatures, retention time and chemical composition of the raw meal. It can be assessed according to the following formulae, which are derived from the so-called Bogue matrix and are valid provided that the mineral phases occur chemically pure [14]:

$$\mathrm{C_3S} = (4.071\ \times \mathrm{CaO}) - (7.600 \times \mathrm{SiO_2}) - (6.718 \times \mathrm{Al_2O_3}) - (1.430 \times \mathrm{Fe_2O_3}) - (2.852 \times \mathrm{SO_3}) \quad (1\text{-}1)$$

$$\mathrm{C_2S} = (2.867 \times \mathrm{SiO_2}) - (0.7544 \times \mathrm{C_3S}) \quad (1\text{-}2)$$

$$\mathrm{C_3A} = (2.650 \times \mathrm{Al_2O_3}) - (1.692 \times \mathrm{Fe_2O_3}) \quad (1\text{-}3)$$

$$\mathrm{C_4AF} = (3.043 \times \mathrm{Fe_2O_3}) \quad (1\text{-}4)$$

1.2.3 Cement Grinding

The last step in cement production is the blending and grinding. For the production of ordinary Portland cement, the clinker is ground together with sulphates such as gypsum or anhydrite. Blended Portland cements are mixed with further additives like fly ash, blast furnace slag or fillers. Table 1.I shows the additives for different cement types. Mills used for cement grinding are, as for the raw meal preparation, tube mills or vertical roller mills. Afterwards the cement is stored in silos or packed and dispatched [10].

Table 1.I: Cement classification according to EN 197-1 [15]

Class	Designation	Clinker Content
CEM I	Portland cement	> 95 %
CEM II	Portland composite cement	65-94 %
CEM III	Blast furnace cement	5-64 %
CEM IV	Pozzolanic cement	45-89 %
CEM V	Composite cement	20-64 %

Standard EN 197-1 [15] Cement defines 27 cement products and their constituents. It also includes requirements on mechanical, physical and chemical parameters.

1.3 Mannersdorf Cement Plant

This thesis addresses the Mannersdorf Cement Plant, which is operated by Lafarge Zementwerke GmbH. It is located in the East of Vienna, Austria, near the Leitha mountain range, which serves as a source for raw materials. The plant produces 2,600 t clinker/ day and the kiln was operating for 7,691 hours in 2017. Apart from the minerals extracted from the limestone quarry and the clay pit, a variety of alternative raw materials such as crushed bricks or mill scale is used. Because the clinker production is realised via the dry process route, the plant is equipped with a five-stage double line suspension preheater, an inline precalciner and a 60 m long rotary kiln (see Figure 1.3). A main burner with a satellite burner at the head of the rotary kiln and the precalciner, where the fuels are dropped into the hot gas stream, consisting of the kiln flue gas and tertiary air from the cooler, deliver the process heat. The exhaust gas from the preheater is headed to the raw mill, where it is used to dry the raw meal, whereas the exhaust gas from the grate cooler is used in the cement mill. A rough scheme of the material flow in Mannersdorf is shown in Figure 1.5.

A new precalciner was implemented to the existing kiln and preheater in March 2017 to increase the alternative fuel rate together with an enhanced clinker quality. To keep down the chlorine content of the clinker and to avoid the circulation of alkalis, the system is equipped with a chlorine bypass located above the kiln inlet. With these installations, the plant pursued the aim of maximising the alternative fuel rate to more than 80 % and thereby achieving neutral thermal energy costs. This target was accomplished with a fuel mix containing petroleum coke, coal, used oil, fine and coarse plastic, sunflower shells and impregnated fuel (ISF), which consists of hazardous workshop waste. Fuel oil extra light is used only for the start-up procedure. Figure 1.6 provides a detailed description of the fuel mix as burned in the year 2017. Of the 2.9 PJ of thermal energy that were consumed in 2017, 42 % of the heat was injected at the main burner and 58 % at the precalciner.

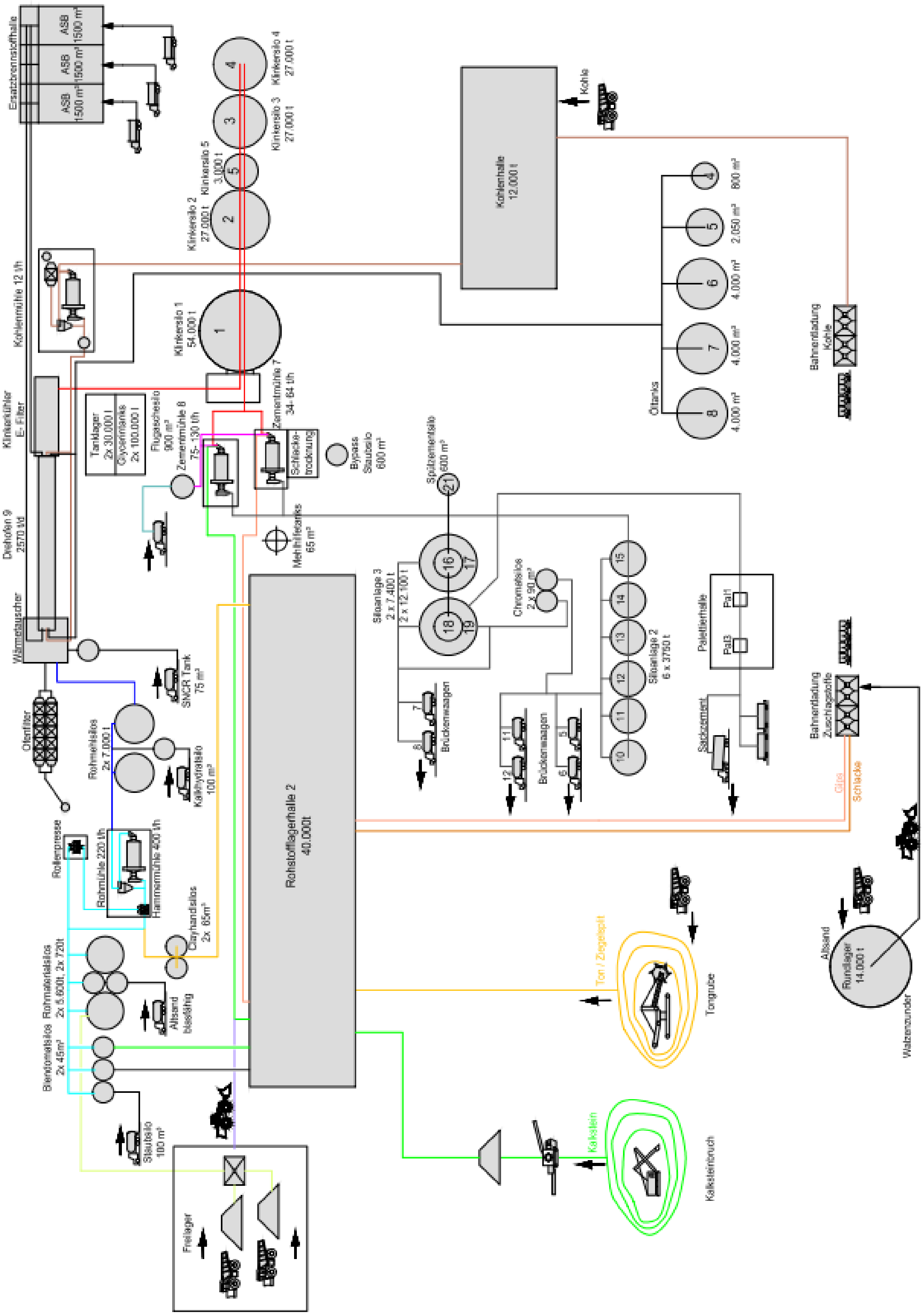

Figure 1.5: Plant overview and material flow

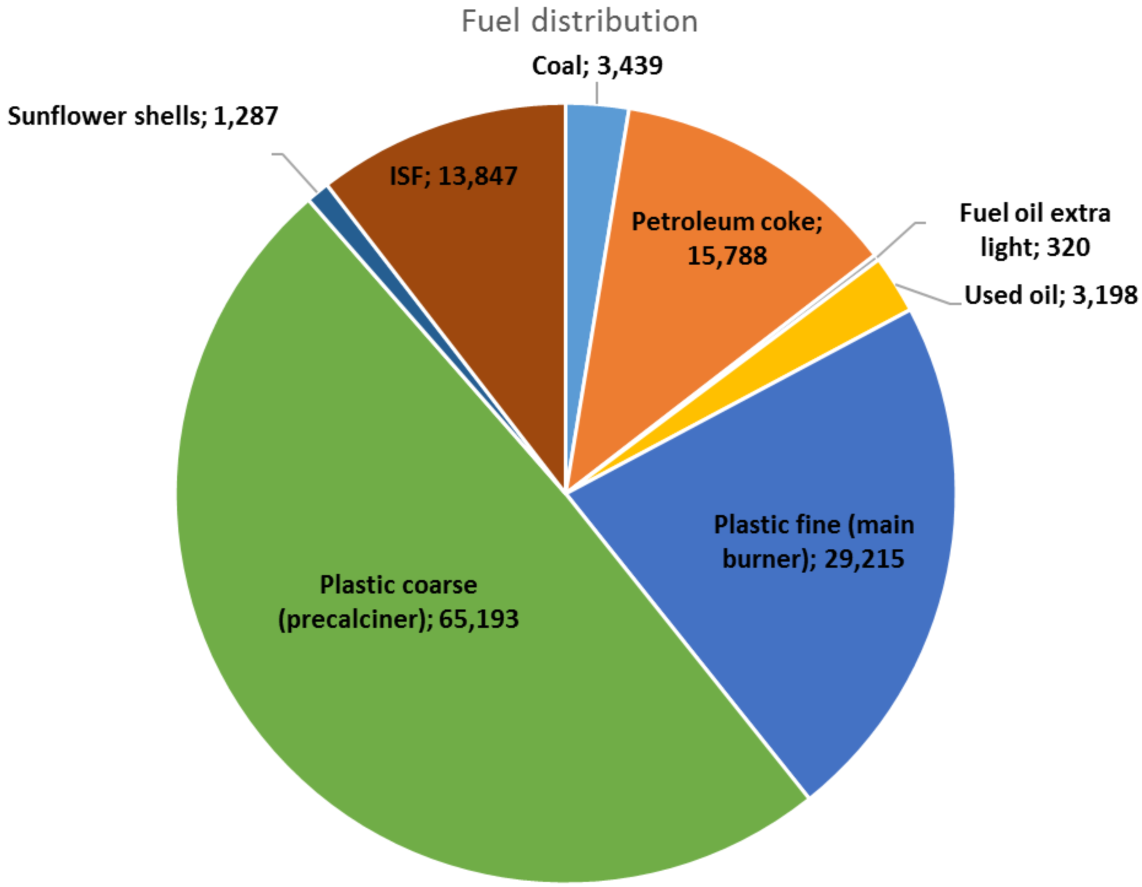

Figure 1.6: Fuel consumption in the year 2017, t/year

2 Status Quo and Developments in the Industry

The topic of energy efficiency, usage of alternative fuels and reduction of CO_2 emissions in cement plants is not a new one, therefore the following chapter summarises different approaches and proceedings, and gives an understanding of the legal and technical framework in which the cement industry is operating.

2.1 Legal Framework

Concerning European industries, the European Union (EU) pursues ambitious targets when it comes to energy consumption as well as environmental and climate protection. As a result, bundles of legal framework and measures have already been enacted to meet those targets. Hereinafter, the most important targets, communications and directives of the European Union and corresponding legislation of the Republic of Austria are elucidated. However, this chapter should not only deal with actual legislation but also give an overview over current developments and an outlook on future challenges that the industry will face. These policies will affect especially the energy and emission intensive industries as the steel and the cement industry and call for new strategies.

2.1.1 Emission of Greenhouse Gases

In 2008, the European Commission communicated the 20 20 targets [6], its climate strategy, in which the European Union set two key targets:

- A reduction of 20 % in greenhouse gases and

- A share of 20 % renewable energy in the EU by the year 2020 from 1990 levels.

The reduction of greenhouse gas emission shall be realised by an increase in energy efficiency to save 20 % in primary energy consumption accompanied by an enhanced emission trading system [6].

According to Directive 2012/27/EU on energy efficiency [9], a reduction in primary energy consumption is not only necessary to limit dependence on energy imports and to mitigate climate change. It should also promote innovative technologies, improve the competitiveness, boost economic growth and create high quality jobs in the energy efficiency sector. A reduction of 20 % in primary energy consumption corresponds to savings of 368 million tonnes of oil equivalent as compared to projections for 2020, which account for an energy consumption of 1842 million tonnes of oil equivalent. This directive also includes the obligation for large enterprises to undergo energy audits taking into account international and European standards on a regular basis [9].

In order to continue its policy, the framework on climate and energy [8], which builds on the 2020 targets, was communicated by the European Commission in 2014 and provides

- A cut of 40 % in greenhouse gas emissions compared to 1990,
- 27 % renewable energy and
- An increase of 27 % in energy efficiency.

In the long term, the objective is to reduce greenhouse gas emission by 80 % until 2050 compared to 1990 levels to limit global warming to a maximum of 2 °C, whereby a reduction by 83 to 87 % should be achieved by the industrial sector, according to the European Commission. Tools to reduce emissions are advanced processes and equipment as well as carbon capture and storage [7].

A major instrument in the European climate and energy policy is the Emission Trading System (ETS), which originates from the Kyoto Protocol of the UN Framework Convention for Climate Change. It operates in 31 countries and includes 11,000 installations, including power stations, industrial plants and airlines, which are accountable for 45 % of the Energy Emissions in the EU. The ETS follows a trading approach to link the greenhouse emission targets to economic aspects. According to the EU ETS [16] Handbook, the system can be described as follows: EU-legislators generate allowances, which contain the right to emit 1 tonne of CO_2 equivalent and reduce the number by 1.74 % per year. A part of the allowances is distributed to the industry, while the rest is sold through auctions. If a participant's greenhouse gas emissions exceed his allowances during a year, he has to acquire allowances from another participant or through auctions. Fines for not complying with the ETS account for 100 EUR/t CO_2.

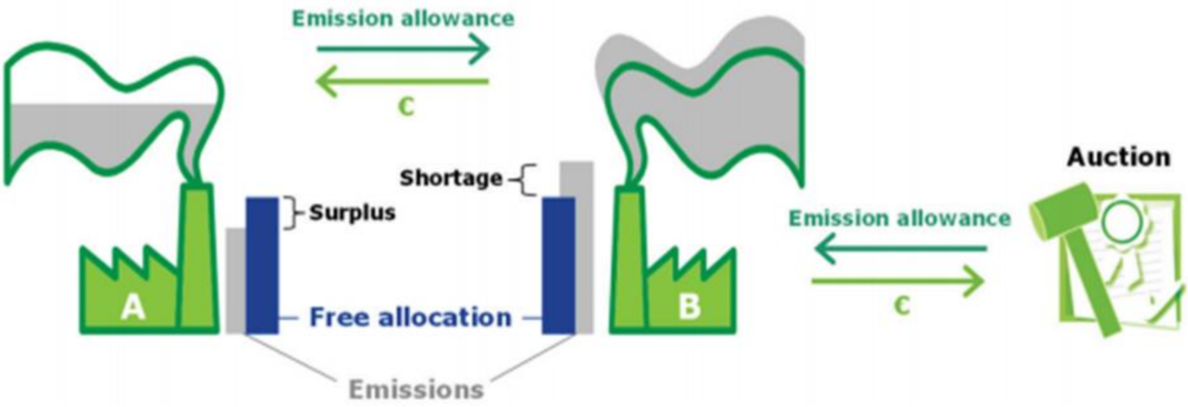

Figure 2.1: Scheme of the mechanics of the EU ETS [16]

Figure 2.1 describes the basic mechanics of the system. Auction platforms for CO_2 allowances are the European Energy Exchange (EEX) in Leipzig and the ICE Futures Europe in London. The price development for allowances at the EEX for the last five years can be abstracted from Figure 2.2. Prices are given in Euro per ton CO_2 equivalent.

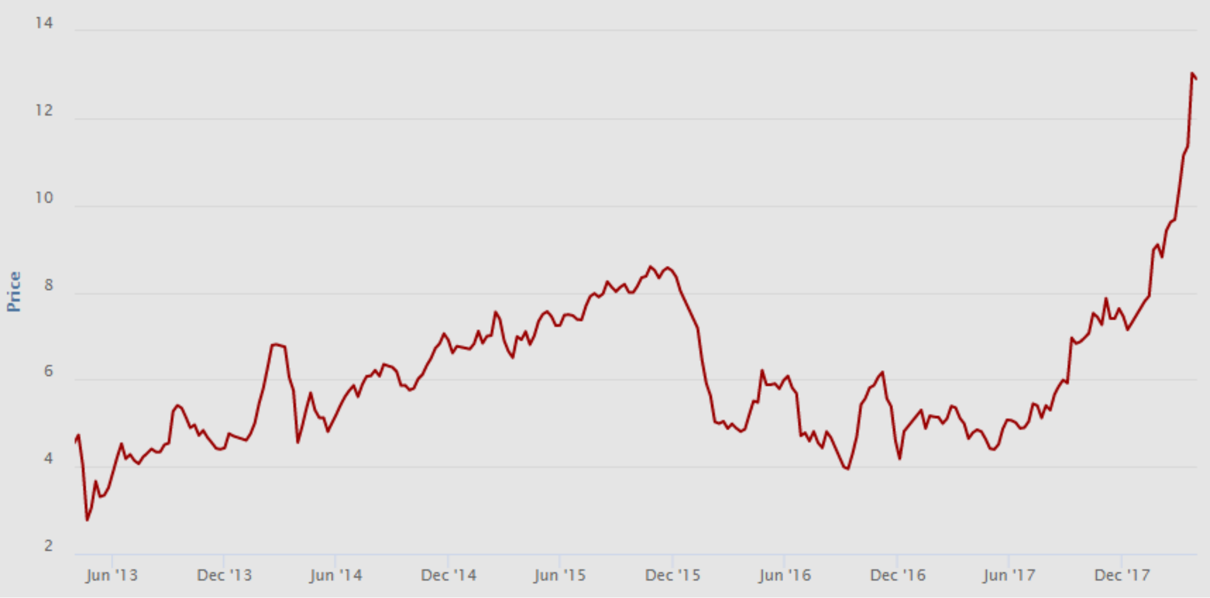

Figure 2.2: Price development for emission allowances, EUR/t CO_2 equivalent [17]

In this context, it has to be stated that the framework predetermined by the EU has to be broken down into domestic law, which shows a broad range of variance for its member states. In Austria, the EU 2020 targets are contained in the Energy Efficiency Law, which aims for a decrease of primary energy demand and thereby a reduction of greenhouse gas emissions as well as an incentive for technological innovation and economic growth. In the year 2020, the total end energy consumption should not exceed 1050 PJ, which corresponds to a cumulative reduction of 310 PJ. Companies with more than 249 employees or a turnover of more than 50 Million Euro or more than 43 Million Euro of total assets are obliged to carry out four-yearly energy audits or to introduce an energy management system according to EN 16001 or ISO 50.001 and to forward the results to a national monitoring authority. Smaller companies have to utilize energy consulting on a regular basis and forward the outcome to the mentioned authority [18].

2.1.2 Emission of Pollutants

According to the Directive on the reduction of national emissions of certain atmospheric pollutants, the member states committed themselves to cut down on emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), non-methane volatile organic compounds (VOC), ammonia (NH_3) and particulate matter (PM) to guarantee an air quality level that has no negative impact on the human health or the environment. For Austria, the directive provides a reduction of 41 % of SO_2, 69 % of NO_X, 36 % of volatile organic compounds, 12 % of NH_3 and 46 % of fine particles in the year 2030 compared to the base year 2005 [19].

The Austrian Waste Incineration Act determines limit values for pollutants that may originate from the combustion of waste. This regulation applies for cement plants using alternative fuels. Each plant is allowed to conclude individual agreements on emission limits with the responsible authority. Emission limits for the Mannersdorf plant are enumerated in Table 2.I and include particulate matter (PM), total organic carbon (TOC), ammonia (NH_3), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and Mercury (Hg). Typically, there are limits for half-hour, daily and yearly average emission values [20].

Table 2.I: Pollutant limits [20]

Pollutant	Half-hour average	Daily average	Yearly average
PM	yes	20 mg/Nm³	20 mg/Nm³
TOC	yes	120 mg/Nm³	120 mg/Nm³
NH_3	-	30/40** mg/Nm³	30/40** mg/Nm³
SO_2	yes	350 mg/Nm³	350 mg/Nm³
NO_x	yes	200/500* mg/Nm³	200/500* mg/Nm³
Hg	-	0.05 mg/Nm³	0.03 mg/Nm³

(Dry flue gas, referred to 10 % oxygen, * without SCR, ** without raw mill or SCR)

2.2 Fuels

Energy costs account for 30-40 % of the total cement production cost [21]. Hence, fuel selection is an important setscrew when it comes to competitiveness in the industry. Furthermore, the fuel types show a broad variety of emission intensities [22].

2.2.1 Conventional Fuels

Common fuels used in the cement industry are fossil fuels such as coal, petroleum coke, fuel oil and natural gas [23]. Table 2.II shows the average net calorific values (NCV) and the specific carbon dioxide emissions for gaseous, liquid and solid fossil fuels. Approximately 40 % of the total CO_2 emitted in the cement production process originates from burning fuels. However, the fuels have a significant impact on the greenhouse gas emissions. CO_2 emissions are much higher for petroleum coke and coal than for natural gas, which is not used extensively in today's operation despite its low emission intensity [22].

Table 2.II: Average NCV and emission intensity for fossil fuels [22, 24]

Fuel	NCV [kJ/kg]	Specific CO_2 emission [kg CO_2/GJ]
Fuel oil	42.373	77.4
Natural gas	47.100	56.1
Coal	26.997	94.6
Petroleum coke	32.010	97.5

Various locations and technologies are qualified to feed fuel to the kiln system. Common inlet points are [10]:

- Main burner at the rotary kiln outlet
- Feed chute at the rotary kiln inlet
- Secondary burner at the riser duct
- Burner or feed chute at the precalciner

In the past, conventional fuels were the means of choice for firing rotary kilns, but as the industry has to cut down on costs, a wide range of fuels is delivering the required heat for the clinker burning process [21]. Especially the European cement industry has advanced in replacing fossil fuels with waste-derived fuels. Some plants reach substitution rates of more than 80 % [10].

The fuel mix of the German cement industry in the years from 2010 to 2016 is summarized in Table 2.III. In total, the energy consumption increased from 88.1 million GJ/year in 2010 to 91.2 million GJ/year in 2016. Alternative fuels accounted for 65 % in 2016 [25].

Table 2.III: Fuel consumption of German cement plants in million GJ/year [25]

Fuel	2010	2011	2012	2013	2014	2015	2016
Coal	9.0	10	9.8	7.8	8.9	8.1	8.3
Lignite	20.7	23.7	22.3	19.7	19.5	18.7	18.9
Petroleum coke	3.3	2.1	3.2	3.2	4.1	3.4	3.2
Fuel oil heavy	0.6	0.4	0.3	0.2	0.2	0.3	0.6
Fuel oil extra light	0.3	0.2	0.7	1.2	0.7	0.7	0.6
Natural and other gases	0.1	0.2	0.2	0.3	0.5	0.4	0.5
Other fossil fuels	0.4	0.1	0.1	1.4	< 0.1	0.3	< 0.1
Total fossil fuels	34.4	36.7	36.6	33.8	33.9	31.9	32.1
Total alternative Fuels	53.7	57.7	57.3	56.6	58.6	58.2	59.1

2.2.2 Alternative Fuels

Due to the energy intensity of the manufacturing process, increasing fuel prices and a scarcity of fuels, the industry has to look for alternative fuels. Alternative fuels or waste-derived fuels are municipal or industrial wastes that are used to substitute conventional fuels. The type of fuels used depends on incineration technology, accessibility of fuels and economic aspects. For the alternative fuel, the most important precondition is that the waste, from which it is derived, has some chemical energy content. A side benefit is that the cement industry contributes to find solutions to waste management problems as the clinker production process complies with hazardous waste incineration requirements. Furthermore, rotary kilns offer suitable conditions for the incineration of waste-derived fuels: high temperature, alkaline environment, oxidising atmosphere, good mixing of gases and product, large surface for heat exchange and sufficient retention time. Another advantage is that there are no additional emissions compared to the use of conventional fuels [21].

Properties of alternative fuels that have to be considered are [26]:

- Physical state
- Content of circulating elements
- Toxicity
- Composition and ash content
- Volatile content
- Calorific value
- Physical properties,
- Grinding properties
- Moisture content
- Proportioning technology
- Chlorine content
- Sulphur content
- Polychlorinated biphenyl (PCB) content
- Heavy metals content
- Emissions released

Alternative Fuels can be classified regarding its physical properties as in Table 2.IV, which also includes examples of common fuels.

Table 2.IV: Classification of alternative fuels [21]

Class	Consistency	Examples
1	Gaseous	Refinery waste gas, landfill gas
2	Liquid	Solvents, oils
3	Pulverised, granulated or finely crushed	Saw dust, sewage sludge, granulated plastic, fine crushed tyres
4	Coarse crushed	Wood waste, crushed tyres, rubber or plastic waste
5	Lump	Whole tyres, plastic lumps

While in the precalciner alternative fuel rates up to 100 % are already realised, it is more difficult to reach such substitution rates in the rotary kiln, as it requires an adaption of the combustion process. Besides necessary technical upgrades such as multi-channel burners, and systems to control the combustion behaviour, another challenge is to provide the required conditions to maintain clinker quality [23].

The ashes of some fuels contain metals, which combine with the raw meal and are in further consequence contained in the clinker. Thus, the raw material mixture has to be adjusted to the fuel mix. For fuels with consistent ash contents, this is much easier. To minimise heat losses, the combustion in rotary kilns takes place with few excess oxygen. In order to ensure complete combustion, constant fuel metering and accurate feeding systems are required, which is especially difficult for solid fuels. This is why most of the feed for the main burner is easily combustible material. Another difference between the precalciner and the rotary kiln in this context is the temperature difference: The location, where fuels are fed into the system has an impact on emissions. Fuel that is burnt at the main burner is fully decomposed due to the high flame temperatures of around 2000 °C. Secondary burners reach lower temperatures, which may neither be sufficient to destroy organic compounds nor to bind metals in the clinker. Volatile fuel contents evaporate and thus, emissions of mercury, thallium, cadmium or volatile organic compounds increase. Wastes containing volatile components have to be burnt at zones that reach sufficiently high temperatures [10].

Summarising, fuels that are composed of wastes should comply with environmental protection standards, have a homogenous calorific value for a stable energy input to the kiln, and provide easy handling for transportation, storage and dosing. Furthermore, ash contents have to be monitored and added to the raw meal composition, to meet the desired product quality [21].

Some of the alternative fuels that are deployed in the cement industry are explained below [27]:

- *Used tyres* can be fed to the kiln as whole tyres or as tyre derived fuel. Its high calorific value of 35.6 MJ/kg and the low moisture content make tyres a suitable fuel and due to the negative environmental impact of land filling, combustion is considered the environmentally friendlier option.
- *Municipal solid waste* has a high availability but its properties are difficult to predict due to a high heterogeneity of municipal waste. Therefore, refuse derived fuel is applicable. The heat value of municipal waste varies from 8 to 11 MJ/kg.
- *Refuse derived fuel* is produced from municipal waste through separation, sorting, size reduction, blending and drying and, as a consequence, has a higher calorific value of 15 to 20 MJ/kg as well as more homogenous properties.
- *Meat and bone meal* has a calorific value of 14.47 MJ/kg, which makes it appropriate for combustion in cement kilns. A disadvantage is its high moisture content of about 70 %. The drying of the meal increases the process cost.
- *Plastic waste* is, such as municipal waste, available in large volumes and has a calorific value ranging from 29 to 40 MJ/kg, but the impact of the chlorine content of PVC on the clinker quality and the emissions have to be considered.

- *Sewage sludge* is one of the products of wastewater treatment plants. Due to its high moisture content, the sludge has to be dried to a moisture content of about 1 % before it is burnt in the dry process. The calorific value is dependent on the origin of the sludge and ranges from 9 to 29 MJ/kg.
- *Solvent and spent oil* are available as waste of industrial, automotive, railway and marine applications. Since the fuel is present liquidly and homogenous, it can be fed through oil firing systems in the main burner or the calciner. The calorific value is 29-36 MJ/kg.
- *Agricultural biomass* can include wastes from rice, corn, nut, coffee and palm farms, and is used rather in developing countries. The calorific value varies quite strong between 14 and 21 MJ/kg and the moisture content lies between 6 and 12 %. The big advantage of biomass is that it is CO_2 neutral, because the plant incorporates the same amount of CO_2 during its lifetime, as it releases in the furnace. The difficulty with biomass is that it is not permanent available, since agriculture follows the seasons.

There are differences in the notation of waste derived fuels, which are difficult to overview because of the wide range of fuels and suppliers. Regarding the fuels used in Mannersdorf, it was chosen to maintain the internal nomenclature in the following chapters, which is defined in Table 2.V. The NCVs are given as per “Identitätskontrolle 2016”, a fuel analysis carried out by an independent laboratory on a regular basis.

Table 2.V: Fuel nomenclature

Notation	Definition	NCV [kJ/kg]	Application
Pipe 2	High calorific, shredded commercial, industrial and plastic waste	25.6	Main burner
HCF	Shredded tyres/rocket mill material	30.1/25.6	Main burner
Used oil	Used oil of commercial, industrial and municipal origin	43.0	Main burner
Pipe 1* SSW*	Medium calorific, shredded commercial, industrial and plastic waste	17.0	Precalciner
ISF	Contaminated waste from mechanical waste treatment, plastic, wood, paper, cardboard	21.7	Precalciner

(* SSW and Pipe 1 have the same quality but different dosing systems)

In this context, it has to be stated that coal is the common internal name for fuels coming from the coal mill. In fact, the used fuel is petroleum coke.

2.3 Thermal Energy Consumption

While the theoretical energy needed for clinker burning stays the same, the actual energy consumption shows wide variations depending on the applied technology. Some measures to cut down on energy consumption are listed in chapter 2.3.2.

2.3.1 Theoretical and actual thermal energy consumption

The chemical reactions that take place to form clinker as well as the drying and preheating of the raw meal constitute the theoretical thermal energy demand of the clinker burning process. This theoretical consumption amounts to 1700 to 1800 MJ/t clinker [10].

Basic reactions of the clinker production process are the evaporation of moisture, the decarbonation (calcination) of limestone to calcium oxide, and the reaction of calcium oxide with silica, ferric oxide, aluminium oxide and free lime. These constituents combine to form the clinker compounds Alite, Belite, Ferrite and Aluminate (see chapter 1.2.2) [3].

Figure 2.3 shows the reaction sequence, which includes dehydration, calcination and sintering of the raw meal and the corresponding temperature windows for a kiln with a four-stage preheater. The precalciner is positioned between the fourth preheater stage and the rotary kiln. On the abscissa, the high enthalpy demand for the calcination process can be observed.

In fact, the energy consumption is much higher and accounts for 3,000 to 4,000 MJ/t clinker for the dry process, three to six stage cyclone preheater and precalciner, and for 3,100 to 4,200 for MJ/t clinker for preheater kilns without precalciner. The thermal energy demand reaches up to 5,000 MJ/t clinker for special cements (e.g. white cement). Generally, the energy demand is dependent on the following parameters:

- Plant size and design
- Kiln throughput
- Moisture content
- Properties of fuels and raw materials
- Specific calorific value of the fuel

- Type of clinker
- Homogenising and metering of kiln feed
- Process control
- Bypass rate [10].

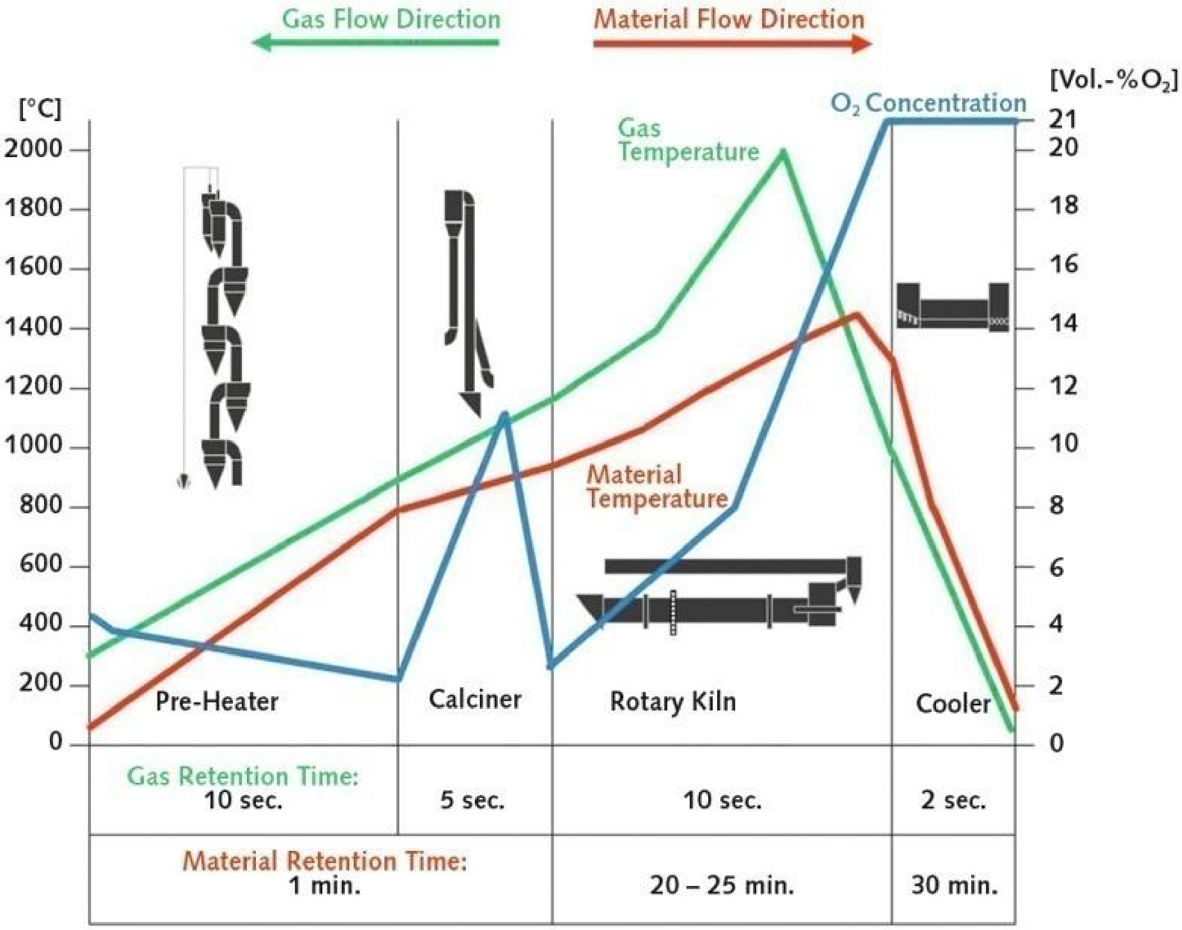

Figure 2.3: Reaction sequence of the clinker burning process [28]

2.3.2 Measures to Improve Energy Efficiency

In their Technology Papers 2017 [4], the Cement Sustainability Initiative (CSI) and the European Cement Research Academy (ECRA) state that the overall thermal energy efficiency of cement kilns is relatively high compared to other processes due to the high potential to utilize hot waste gas streams, such as kiln and cooler exhaust gases, for raw material and fuel drying. The weighted average specific thermal energy d emand for a dry kiln with preheater and precalciner dropped from 3,605 MJ/t clinker in the year 1990 to 3,380 MJ/t clinker in 2014, which is a decrease of 6 %. Parameters that have an impact on the thermal energy demand are listed in Chapter 2.3.1, whereas ECRA quotes the increase in kiln capacity and the installation of additional cyclone stages in the preheater as main reasons for the enhanced energy efficiency. In the paper, it is also mentioned that there is no potential for further significant energy efficiency improvement in sight for state-of-technology plants [4].

According to “Energieeffizienz in der Industrie” [5], further efficiency improvement can be achieved with an adaption of the burner design for efficient combustion of alternative fuels, optimization of the fuel mix and its quality and a sophisticated kiln control system, as well as primary air heating and oxygen enrichment. An additional benefit is that improvements in these areas are positively affecting the product quality [5].

In their study on energy auditing and conservation opportunities in pyroprocessing units of cement plants, Kabir et al. [29] propose the use of exhaust gases for the preheating of raw materials in the raw mill and electricity generation via a waste heat recovery steam generator to recover the sensible heat of the exiting gas streams. Benefits of the raw material preheating are the evaporation of moisture and enhancement of the grinding efficiency, the electricity generation results in enormous electricity cost savings. To reduce the convection and radiation losses at the rotary kiln, the study contains the recommendation to coat the kiln with glass wool as an insulation material and a secondary shell. Further suggestions are the tightening of all equipment to avoid false air, improvement of the combustion system and the development of alternative pyroprocessing concepts [29].

The BAT document for cement production [10] concludes that a plant with the standard technique configuration, which is defined as four to six preheater stages and precalciner, should have a short-term energy demand of 2,900-3,300 MJ/t clinker and average energy consumption values that are 160-320 MJ/t clinker higher. According to the BAT document, legal requirements, local circumstances and cost reduction result in a driving force throughout the industry to improve the energy efficiency. This document also includes the following recommendations on process and equipment to increase energy efficiency [10]:

- *Clinker cooler*: The grate cooler is considered the most efficient cooler technology. It should exhibit a high grate flow resistance and have a controllable cooling air supply for each section.

- *Rotary kiln*: To guarantee minimal energy consumption, the kiln should be optimized in terms of length-diameter ratio, firing system and process control, and be operated at stable conditions, slightly oxidizing atmosphere and minimized air leakage.
- *Precalciner*: Uniform raw meal distribution in the riser duct and near-complete decarbonation are indicators of an efficient precalciner. Furthermore, coating due to alkali has to be prevented and the resulting pressure drop should be kept as low as reasonably possible.
- *Preheater*: An efficient preheater provides a high cyclone collection rate and allows a uniform distribution of the raw meal in the gas ducts. As already stated for the precalciner, the pressure drop at the preheater should account for a minimum. For efficient preheaters, the number of cyclone stages lies between three and six. The ideal number of stages is dependent on throughput and moisture content of the deployed materials. Furthermore, it has to be ensured that the raw meal is divided equally among the cyclone strings.

2.3.3 Energy Balancing

An energy audit is a method to determine the performance of a kiln system, the fuel consumption and the efficiency of fuel utilization. In order to make statements about the energy-related condition of the kiln system, one option is to draw up an energy balance. Thereby, all in- and outflowing enthalpy is equated. According to Kabir et al. [29], the following assumptions have to be made for the energy analysis:

- Steady state operation conditions
- Plant in equilibrium
- Constant ambient temperature
- Negligible air leakage
- Constant material compositions
- Constant surface temperatures

In case of the clinker kiln system in Mannersdorf, Figure 2.4 describes the assembly of the balance that was calculated according to the Excel sheet provided by Lafarge. To calculate the heat balance, the temperature and mass flow of in- and outflowing materials and gases has to be measured as well as the wall losses. In this context, it has to be pointed out that for the kiln audit carried out in Mannersdorf, the false air, which occurred in significant volumes, was not neglected as mentioned above, but considered in the heat balance. Chapter 3.1 contains detailed information of the audit procedure and the heat balance calculation.

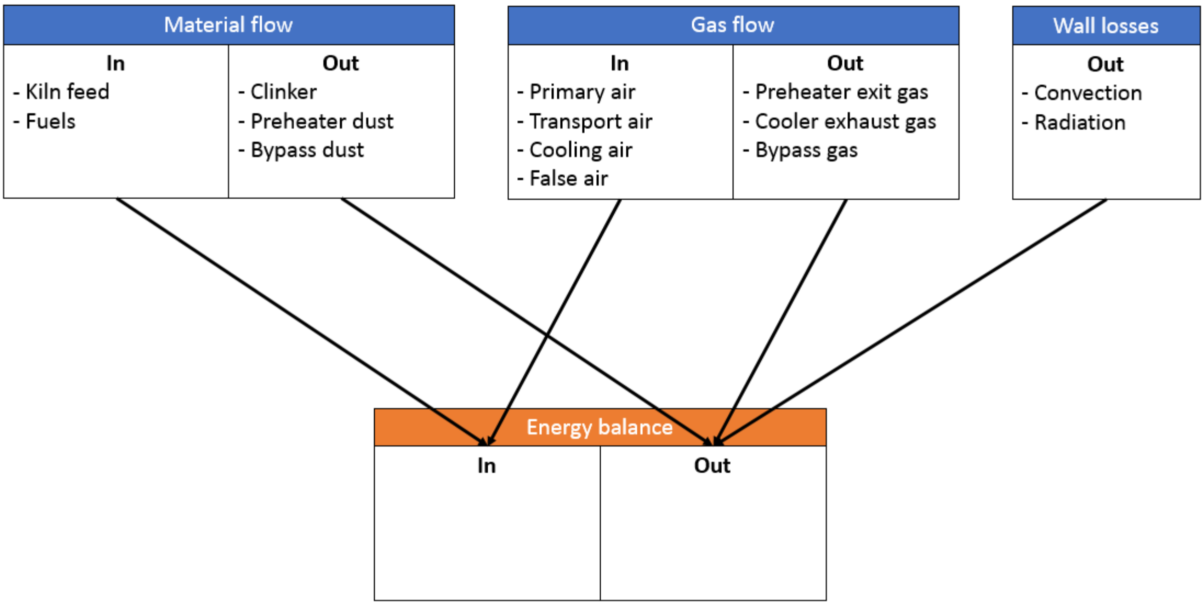

Figure 2.4: Simplified calculation scheme of an energy balance

Combustion heat of fuels and total organic carbon in the raw material (TOC) can be calculated after equation (2-1), whereby the sensible heat is calculated after equation (2-2). $\dot{\mathrm{Q}}$ represents the heat flow, $\dot{\mathrm{m}}$ the mass flow, NCV the net calorific value or specific combustion heat, c_p is the specific heat capacity at constant pressure, and θ is the temperature [29].

$$\dot{Q}_{combustion,i} = \dot{m}_i NCV \tag{2-1}$$

$$\dot{Q}_{sensible\ heat,i} = \dot{m}_i c_{p,i} \theta \tag{2-2}$$

The formulas that describe the wall losses are explained in chapter 3.1.5. Additionally, the sensible and evaporation heat of the moisture content in the air, the raw materials and fuels has to be taken into account. Finally, the heat of formation of clinker, which is explained in chapter 2.3.1, has to be added to the output side of the energy balance [29].

2.4 Alternative Concepts

A lot of research on energy efficiency and CO_2 abatement was done not only based on state of the art technology but also considering new strategies and processes. In the following chapter, some of these new concepts are suggested as potential future processes.

2.4.1 Electricity Cogeneration

An option to recover the heat of exhaust gases is a waste heat recovery. As displayed in Figure 2.5, the exhaust gas streams of the preheater and the cooler are conducted to a heat exchanger, where the steam for a Clausius Rankine Cycle is generated [30].

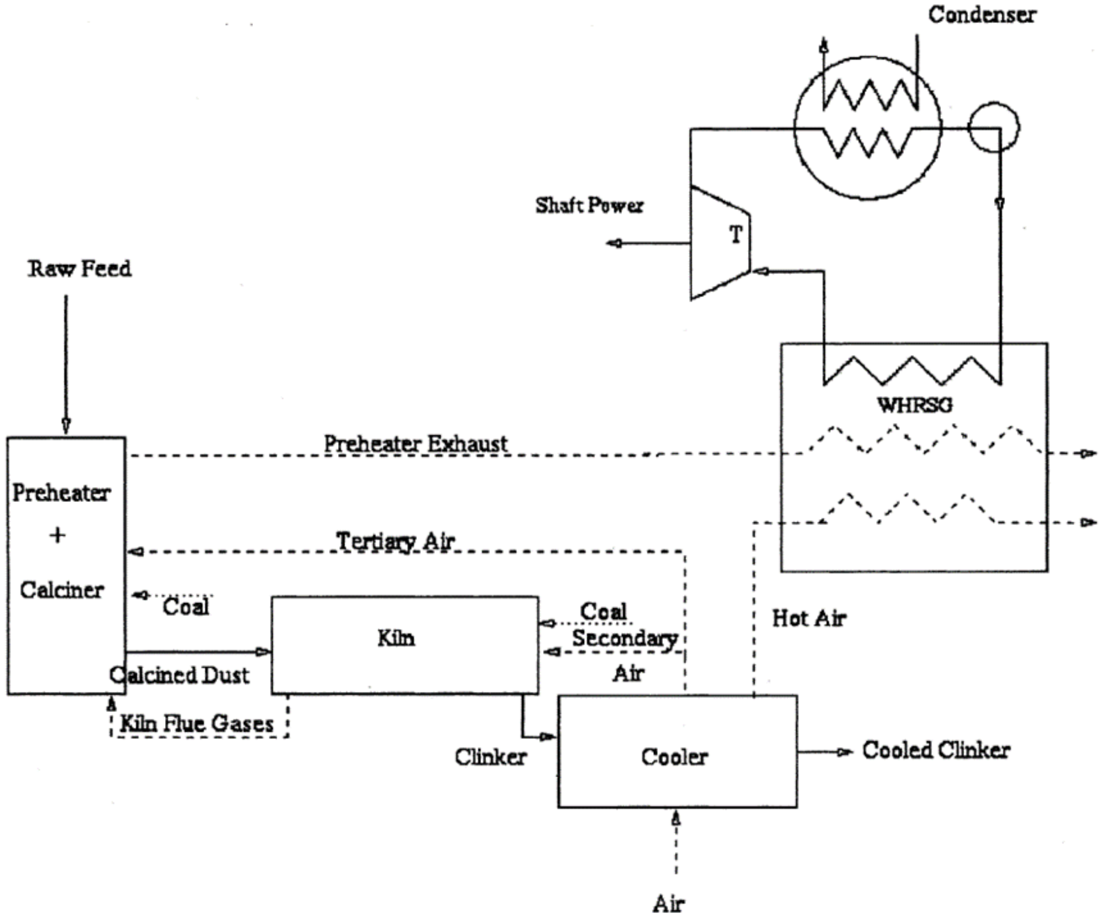

Figure 2.5: Heat flows with implemented waste heat recovery [30]

Usually, the preheater exhaust gases are used to dry the raw material but the excess gas, especially the exhaust air of the cooler can be used either for the drying of fuels or the production of hot water, steam and electric power. If there are heat consumers nearby, it makes sense to produce hot water or steam. Otherwise, power generation is a way to use the heat. Due to the low temperatures of the waste gases, the Clausius Rankine Cycle, which utilizes steam to drive a turbine, has low efficiency factors of 20 to 25 %. Depending on the plant configuration, 8-22 kWh/t clinker can be generated, which is about 16 % of the power consumption of a cement plant. The Organic Rankine Cycle (ORC) can be operated with a wide range of working fluids, which allows the usage of heat sources with lower temperatures compared to the conventional steam cycle. Furthermore, investment costs are less for an ORC installation due to the fact that no super heater is needed. With efficiency factors from 10 to 20 %, 10-20 kWh/t clinker can be produced. Several cement plants were equipped with an ORC installation since 1999, according to CSI and ECRA. Similar yields, namely 10-22 kWh/t clinker, can be expected from the Kalina Cycle, which uses a mixture of NH_3 and water as working fluid. The advantage is that the boiling point of the mixture can be adjusted to the temperature of the heat source [4].

It should be noted that electricity cogeneration is reducing neither energy demand nor emissions but enhances the overall energy efficiency.

2.4.2 Fluidized Bed Process

A Japanese approach to reduce the energy demand for clinker burning, which is proposed in the BAT document on cement production [10], is to apply a fluidised bed reactor for sintering.

The whole plant includes the following units: In the suspension preheater, the raw meal is preheated and calcined. Thereafter, the raw meal is granulated to a size of 1.5 to 2.5 mm in a spouted bed granulating kiln at 1300 °C and subsequently sintered in the fluidised bed sintering kiln at 1400 °C. Instead of a grate cooler, a fluidised bed quenching cooler is deployed to cool the sintered granules down to 1000 °C, until the cement clinker is cooled in a packed bed cooler to 100 °C for storage or transport [10].

The fluidised bed process was carried out in pilot plants with capacities of 20 and 200 t clinker/day. Figure 2.6 illustrates the test assembly with the granulating kiln (SBK), the sintering kiln (FBK), the quench (FBQ) and the cooler (PBC) as well as the feeding points for raw materials, air and fuel. A feasibility study of a plant with a capacity of 3000 t clinker/day claims that the heat consumption can be reduced by 10–12 % compared to a plant with suspension preheater, rotary kiln and grate cooler. Targets for further development besides the reduction of heat demand are NO_X levels of 380 mg/Nm³ referred to 10 % oxygen and a 30 % decrease in costs for construction and installation area [10].

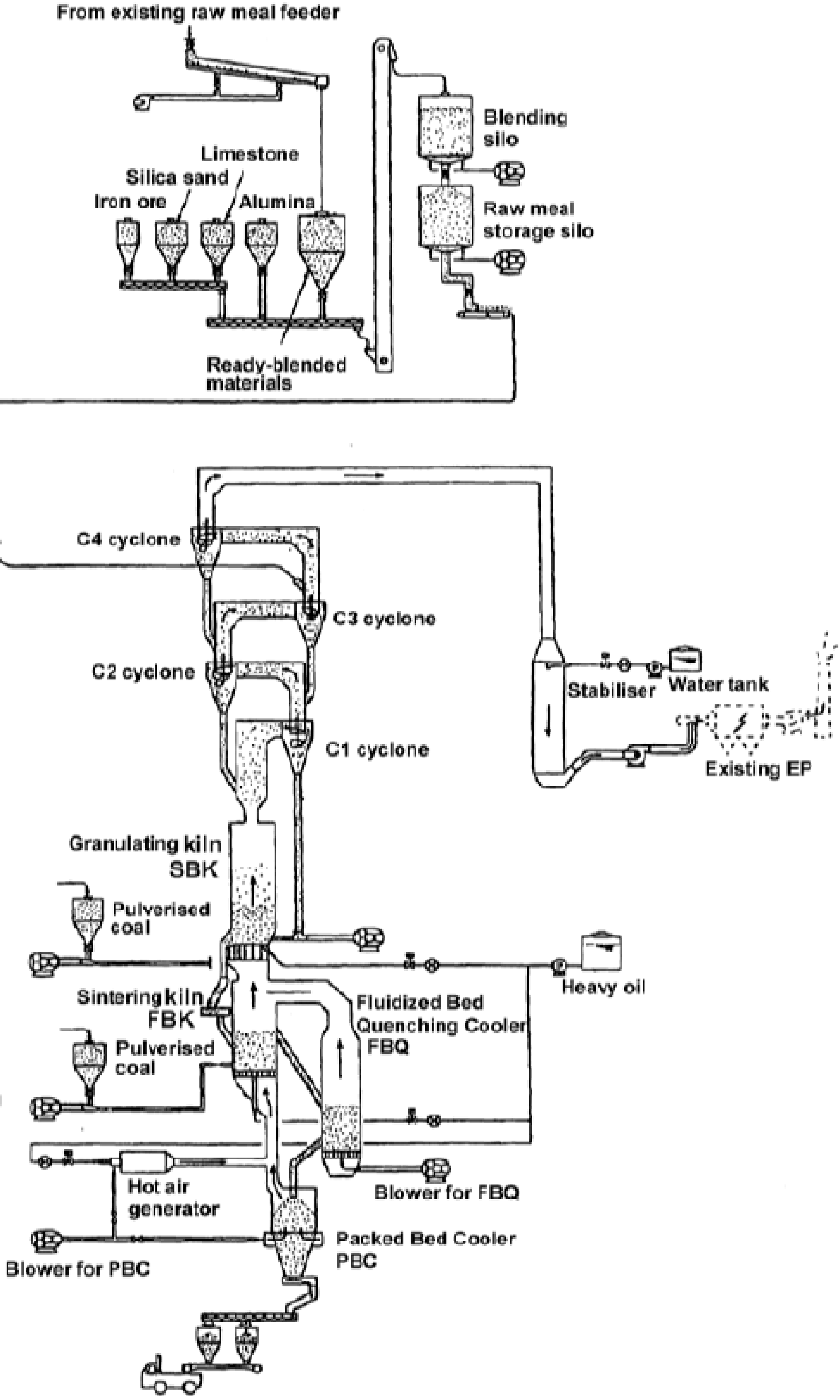

Figure 2.6: Flow scheme of a fluidized bed pilot plant [10]

2.4.3 Oxygen Enrichment

The idea behind this technology is to enrich the combustion air with oxygen. According to the Technology Papers of CSI and ECRA, the enhanced oxygen level increases the energy efficiency, the product quality and allows the use of fuels with lower calorific value. An oxygen enrichment up to 35 % leads to a reduction in specific energy demand up to 5 %. Due to the decrease of the nitrogen content in the combustion air, the adiabatic flame temperature rises. Therefore, the enrichment has to be adjusted to the specifications of the refractory lining and the NO_X formation. The disadvantage is that together with increasing fuel savings, the electric energy consumption of the air separation unit increases. Today, some plants employ the technology to enhance their capacity [4].

2.4.4 Carbon Capture and Storage

The awareness that the cement industry is the second biggest emitter of greenhouse gases after the energy sector leads to discussion of carbon capture and storage (CCS) technologies as an approach to CO_2 abatement. The idea is to separate the CO2 from the flue gas and store it. As most CCS technologies are in research state, the economic feasibility cannot be assessed. Today, costs are estimated to range from 50 to 70 EUR/ t CO_2 [4].

One of the viable processes is the oxyfuel combustion. This technology uses pure oxygen instead of ambient air as primary combustion gas. Therefore, oxygen in the ambient air is separated from the nitrogen and then fed into the kiln through the main burner. Since the combustion with pure oxygen increases the adiabatic flame temperature, a certain amount of exhaust gas has to be circulated to adjust the flame temperature. The CO_2 in the flue gas, which reaches concentrations of 80 %, is separated, purified and compressed in order to avoid any emission. Besides wide changes in the energy balance of the kiln, additional electric energy is necessary for the air separation as well as the CO_2 purification. Other processes that are applicable to capture CO_2 are post-combustion technologies. The advantage thereby is that there are no changes in the clinker burning process. They are based on the separation of CO_2 in the flue gas, which is realised as chemical absorption, membranes, or physical absorption [4].

Criteria for the application of CCS are solutions for the use of captured CO_2, availability of the technology on industrial scale, investment costs, economic and political situation, CO_2 transport infrastructure, public acceptance and legal requirements. Whilst CCS is not advantageous from an energy-related point of view, it is one of the few measures to avoid CO_2

emissions. However, in the light of rising costs for greenhouse gas emission allowances, CCS might become economically viable in the future. Potential applications for the captured CO_2 could be Power to Gas, Power to Liquids, Enhanced Oil Recovery or the production of bio fuels [4].

3 Data Acquisition

The data for the following analysis of the energy efficiency and stability was collected during a kiln audit and a field campaign, or extracted from the online measurement system.

3.1 Kiln Audit

The kiln audit, which was conducted on October 24th 2017, serves as an origin for the following considerations. According to the regulations within the LafargeHolcim Group as well as legal requirements [18], the audit has to be performed on a regular basis. Besides, it provides a status quo, on which the performance of the process can be evaluated and optimisation strategies can be planned. The measurements were conducted by a team of six process and quality engineers and the author of this thesis. The time window of the Audit reached from October 24th, 6 am to October 25th, 6 am.

3.1.1 Balance Border

For the audit mentioned above, the balance border was set between the flue gas outlet or the raw meal inlet of the first cyclone stage on top of the preheater and the exhaust outlet or the clinker conveyor of the clinker cooler. To gather additional information about the process quality, material samples and gas measurements were executed not only at the balance borders, but also throughout the whole process. Figure 3.1 allows an overview over the balance border. The dust that aggregated in the filters of the gas bypass and the preheater exhaust gas was weighed, sampled and added to the material balance together with the raw meal and fuels, which enter, and the clinker, which exits the system. All gas fluxes crossing the system border, including the bypass gas, preheater and cooler exhaust gas, the air provided by the cooler fans, the transport and primary air of the main burner and the estimated amount of false air, were considered in the gas balance. The consolidation of these separate balances results in the heat balance that is discussed in chapter 4.1.1 of this thesis.

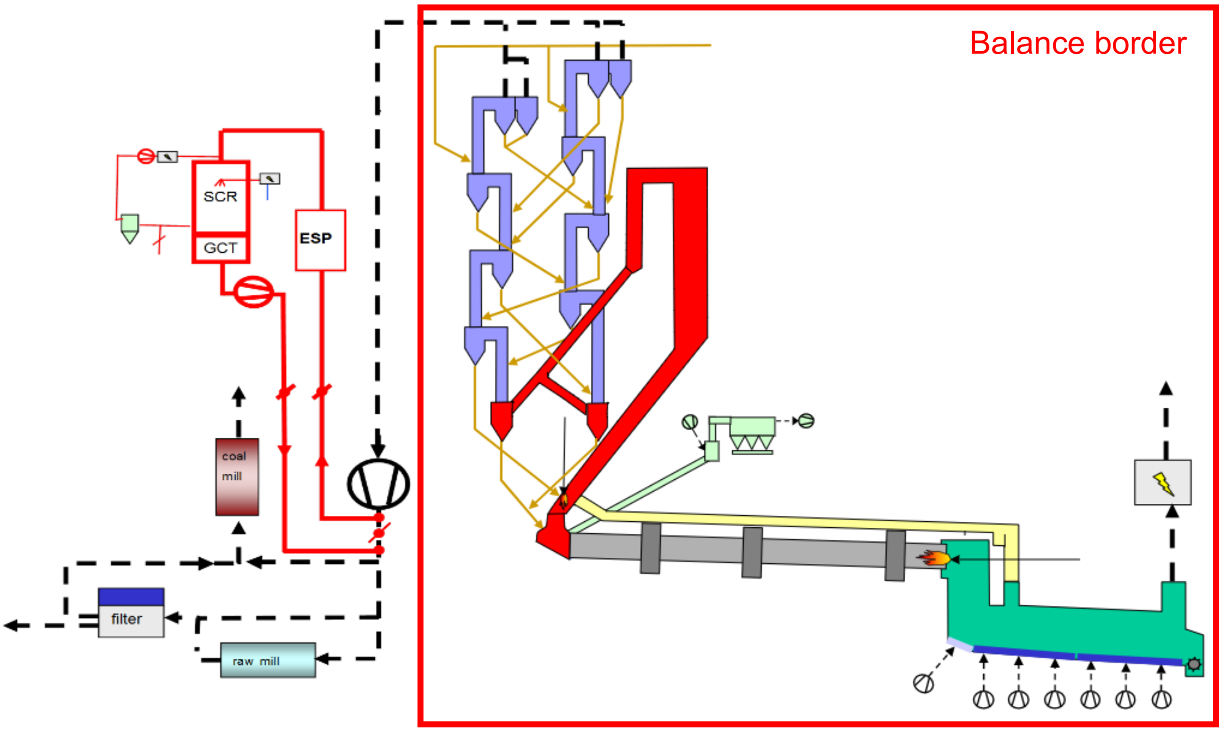

Figure 3.1: Pyroprocessing unit with defined balance border

3.1.2 Operational Parameters

The crucial technical demand was that the kiln is in stable operation for at least 24 hours and that all in- and outbound material, gas and energy flux across the balance border is known. Therefore, all the measurements have to be carried out and all material samples have to be collected during this time, which is the reason for the size of the audit team. The Kiln Master, an automatic kiln control system, was enabled at the audit start with a temperature of 872 °C in the lowermost cyclone stage. The kiln control software adjusts the fuel consumption to reach a predefined temperature after the precalciner, which is used as process variable. The kiln feed rate, which is shown in Figure 3.2, was defined to be 186 t/h at a rotary kiln speed of 3.18 rpm, which results in a residence time of 24.8 minutes in the kiln and a clinker production rate of 102 t/h. The fuel feed rates were pre-set at 2.28 t/h for petroleum coke and 3.97 t/h for SSW at the main burner, and 0.075 t/h for petroleum coke and 15.34 t/h for alternative fuels (see Table 2.V) at the precalciner. This led to a heat input of 62.3 % at the precalciner and 37.7 % at the main burner.

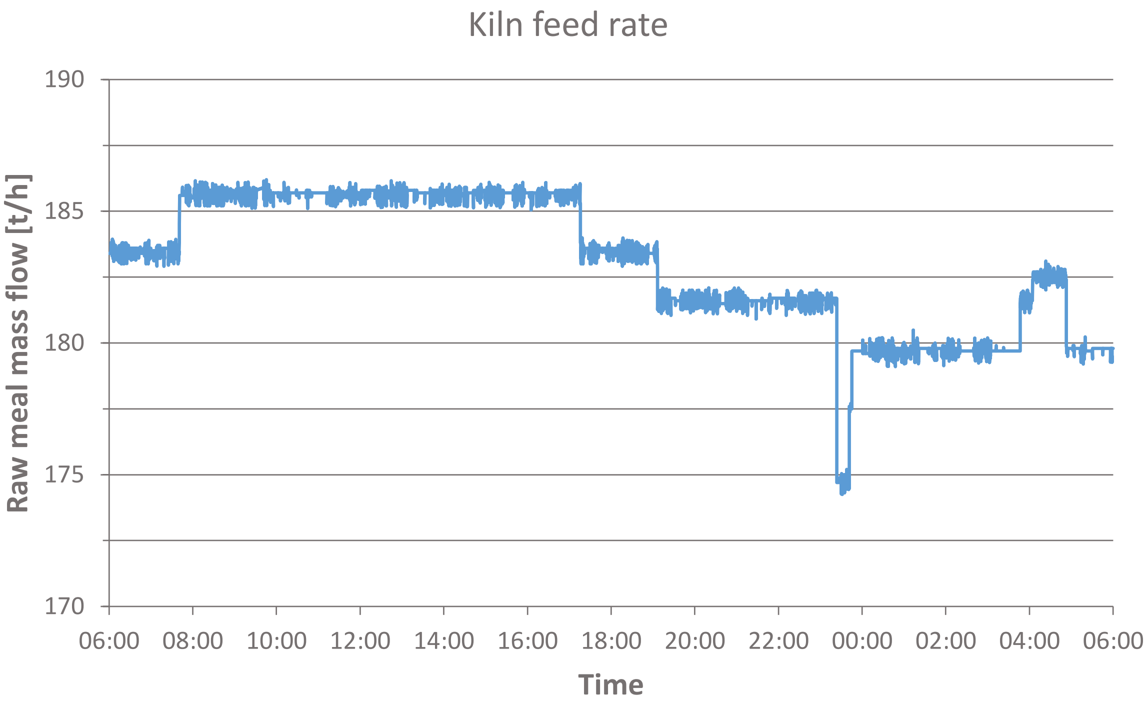

Figure 3.2: Kiln feed rate

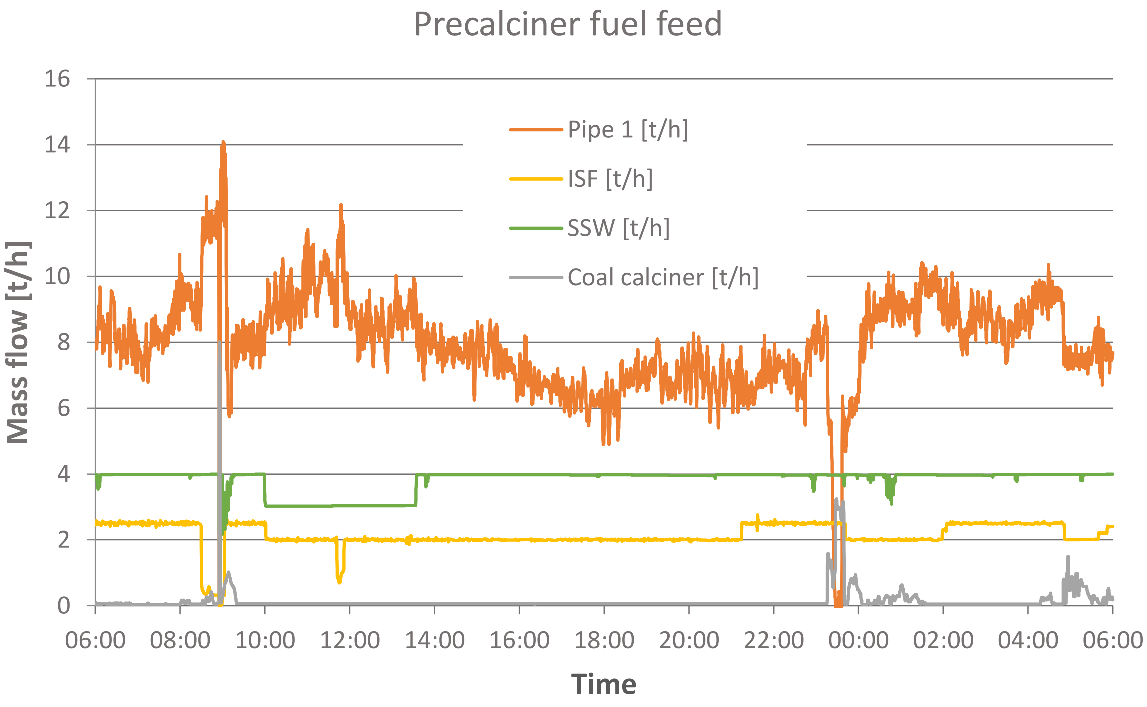

Figure 3.3: Precalciner fuel feed rate

Figure 3.3 and Figure 3.4 depict the mass flow of fuels during the audit recorded by the online measurement system, whereas Figure 3.5 indicates the alternative fuel rate (AFR).

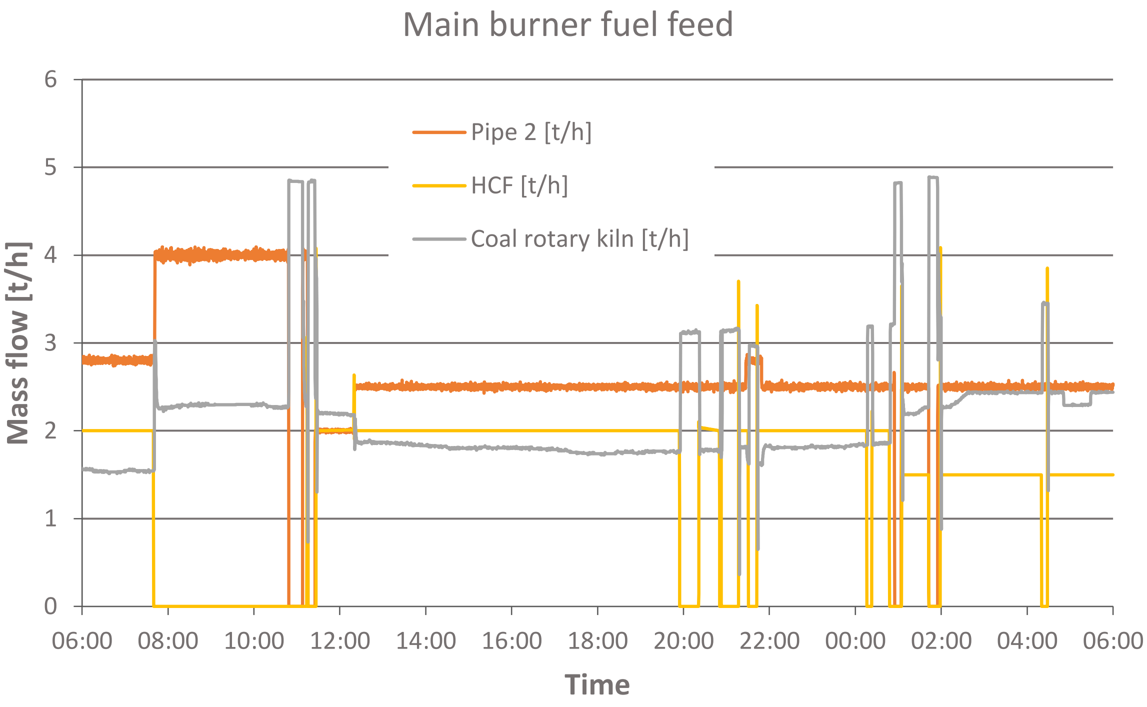

Figure 3.4: Main burner fuel feed rate

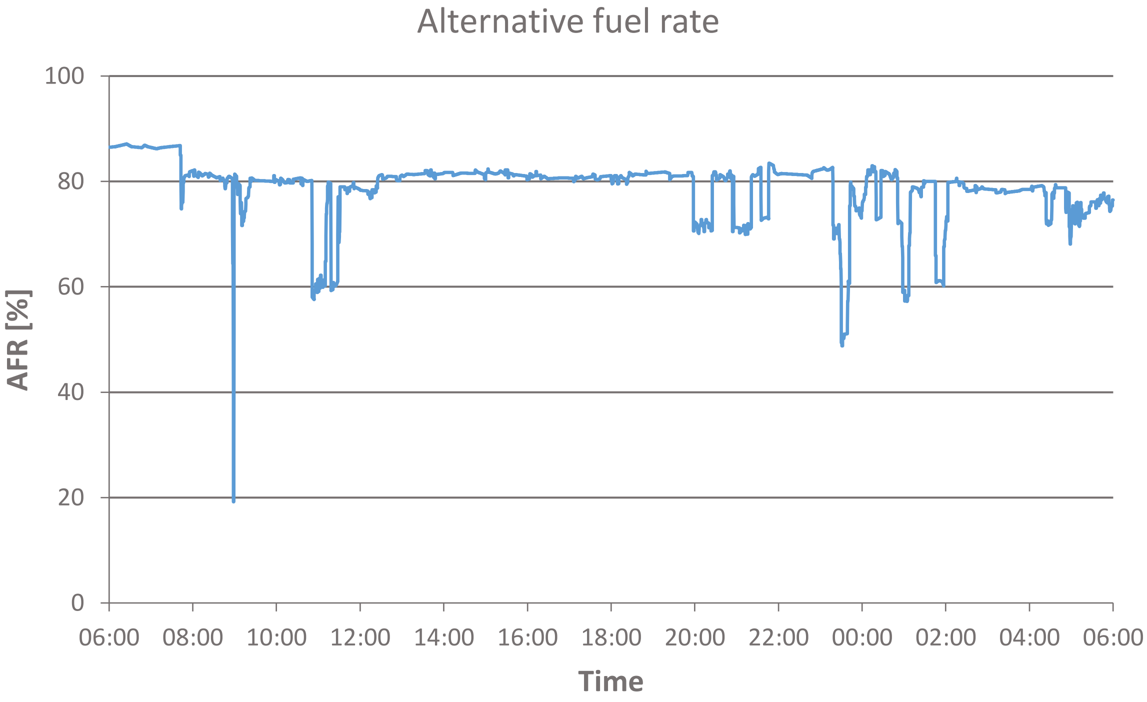

Figure 3.5: Alternative fuel rate

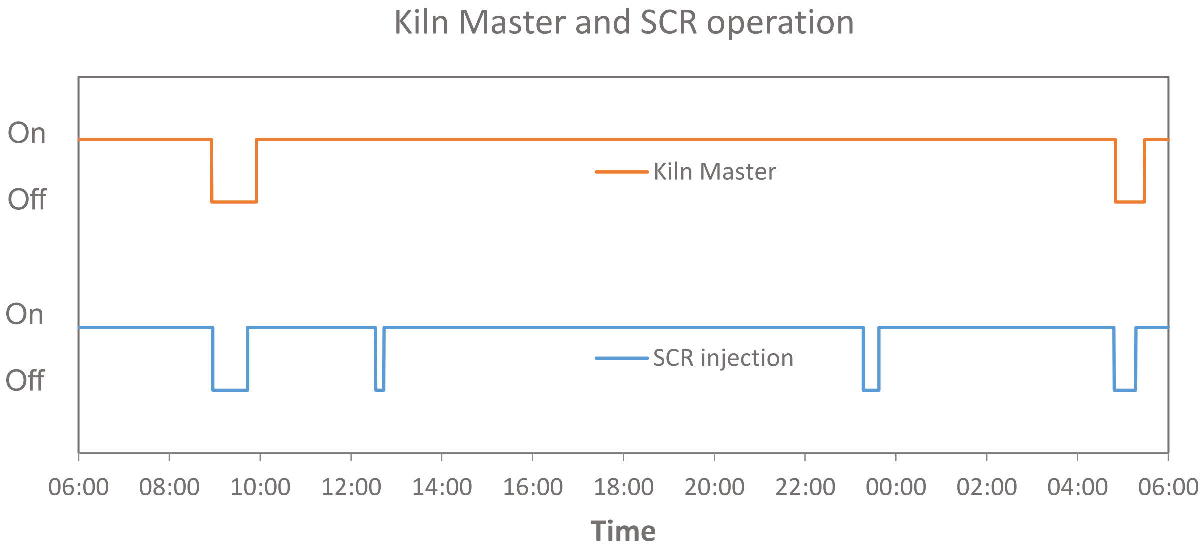

Figure 3.6: Operation status of Kiln Master and selective catalytic reduction (SCR)

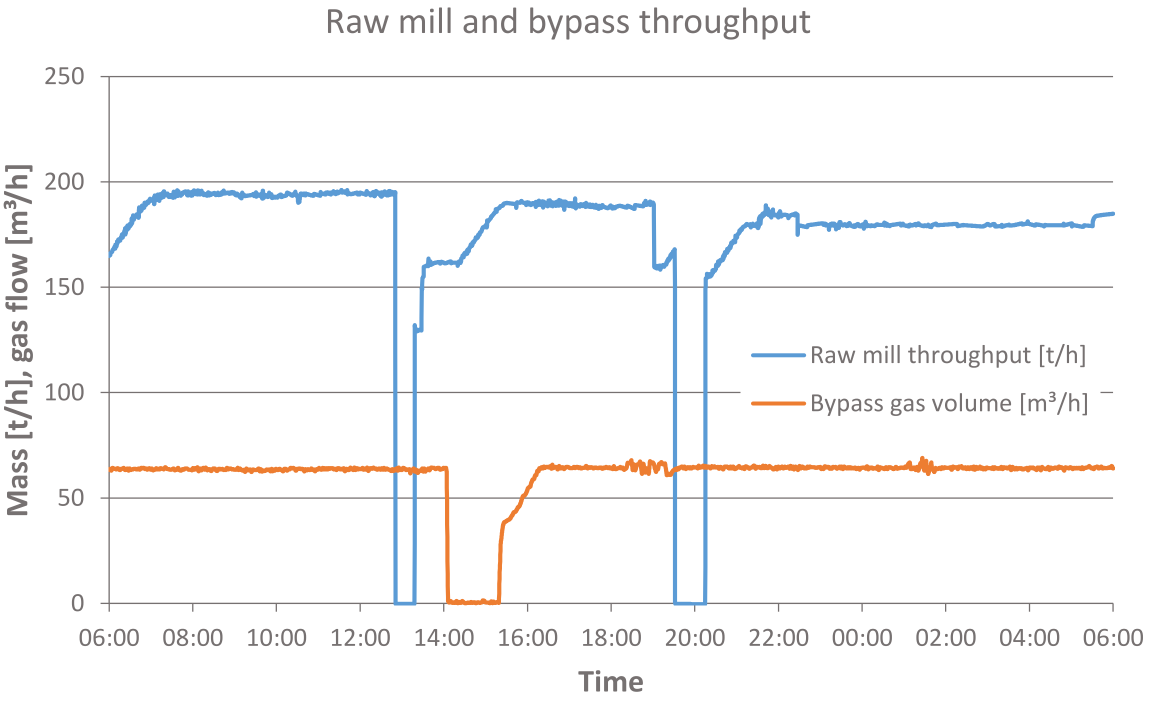

Figure 3.7: Raw mill throughput and bypass gas volumes

Due to a lack of oxygen and a carbon monoxide peak in the precalciner gas, the Kiln Master was deactivated at 9:07 am. Alternative fuels had to be substituted by petroleum coke thrice as a consequence of pipe conveyor malfunctions at 9 am, at 11 am and at 11:16 am. Further occurrences were a bypass stoppage at 2 pm and a deficiency in the selective catalytic reduction (SCR) system after a pressure aberration at 12:33 am, which was started again after

10 minutes. Statuses of the Kiln Master and SCR are summarized in Figure 3.6, those of the gas bypass and raw mill in Figure 3.7.

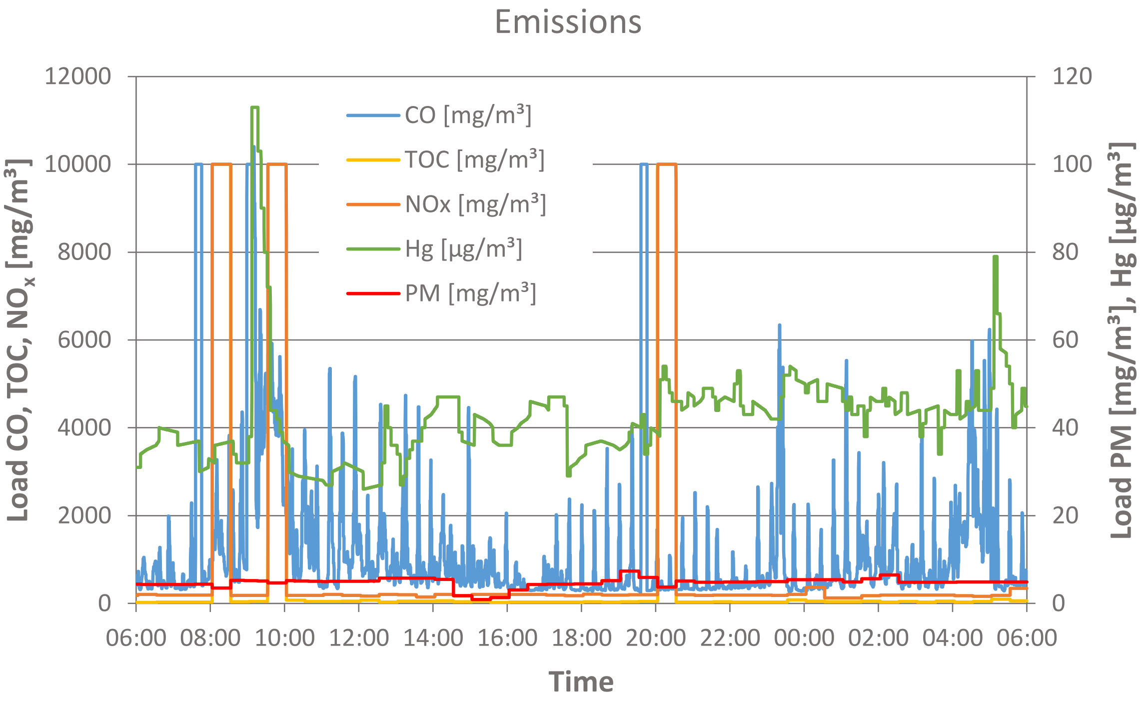

Figure 3.8: Pollutant emissions

Figure 3.8 gives an overview over the emissions, measured by the online system at the chimney including carbon monoxide (CO), total carbon (TOC), nitrogen oxides (NO_x), mercury (Hg) and particulate matter (PM).

3.1.3 Material Flow

Specific heat consumption (SHC) is a key figure representing the heat that has to be injected into the system to produce 1 kg of clinker. During the audit, the specific heat consumption was 3,556 kJ/kg clinker. The fuels were fed at the main burner and precalciner with the actual feed rates, net calorific values (NCV) and waste gas volumes presented in Table 3.I. 42 % of the heat was generated at the main burner using petroleum coke (Coal) and high calorific shredded industrial waste (SSW), whilst 58 % was injected at the precalciner applying a similar fuel mix with lower calorific values (SSW and ISF). The high calorific material is necessary to reach higher adiabatic flame temperatures at the main burner. To allow a more meaningful analysis of the energy efficiency, the combustible content of the raw material has to be added to the SHC. Elements in the raw meal that participate in the combustion are carbon and sulphur with net calorific values of 33.830 GJ/t and 13.120 GJ/t but are not present in the raw material to a large extent as shown in Table 3.I. Due to this fact, the heat generated by TOC and S^{-2} accounts for 1 % of specific heat consumption. Including total organic carbon (TOC) and sulphur (S^{-2}), which indicate the amount of organic carbon and sulphur in the raw material, the specific heat consumption increases to 3,620 kJ/kg clinker.

Table 3.I: Actual fuel mix as burned during the audit

Fuels	Mass flow [t/h]	NCV* [GJ/t]	Waste gas** [Nm³/kg clinker]	Waste gas** [Nm³/MJ]	Ratio of SHC [%]
Main burner					42.0/40.1***
Coal	2.170	32.944	0.18	0.27	19.1
SSW-Pipe2	2.620	19.985	0.13	0.30	14.0
SSW-HC	1.440	18.107	0.07	0.31	7.0
Fall through	0.472	15.294	0.02	0.33	1.9
Precalciner					58.0
Coal	0.142	32.944	0.01	0.27	1.3
SSW-MC	7.661	15.294	0.32	0.33	31.4
SSW-L3	3.667	15.294	0.15	0.33	15.0
ISF	2.140	17.986	0.10	0.32	10.3
TOC	0.086	33.830	0.01	0.27	-
S^{-2}	0.036	13.120	0.00	0.38	-

(*NCV as fired, ** neutral waste gases, ***excluding fall through)

The second group of materials that was fed into the system besides fuels was the raw meal, which had an actual mass flow of 180.77 t/h. Materials exiting the system boundary are the by-products preheater dust and bypass dust, which are separated from the exhaust gas in the corresponding filters, and clinker as the product of the whole process. The chemical content and mass flow of the kiln feed, the main burner and precalciner fuel ash, the clinker as well as the bypass and preheater dust are listed in Table 3.II. A vanishingly low moisture content of 0.2 % in the raw meal is the result of the drying process in the raw mill. Main burner and precalciner fuels were summarised in Table 3.I. The loss on ignition (LOI) is the amount of carbon dioxide and crystal water that is expulsed due to the high temperatures and continuous heat supply. Hence, the raw material input is much higher than the produced clinker. Material samples were collected during the audit period. The chemical composition of kiln feed, fuels, dust and clinker were analysed by the on-site as well as the CTEC laboratory and determined as follows.

Table 3.II: Chemical content of materials entering and exiting the system boundary

	Kiln feed	Kiln fuel	Fall through	Calciner fuel	Preheater dust	Bypass dust	Clinker
Mass flow [t/h]	180.77	6.23	0.472	13.61	22.30	1.00	105.06
				Chemical content [%]			
H_2O	0.20	-	-	-	-	-	-
Sulphur	-	0.29	0.82	0.73	-	-	-
Ash	-	8.95	15.92	16.28	-	-	
Cl	0.04	0.51	0.51	0.49	0.28	8.24	0.13
				Ash as fired			
SiO_2	13.37	28.75	26.60	26.43	8.79	13.9	21.3
Al_2O_3	2.77	23.89	14.4	15.98	2.75	3.08	4.63
Fe_2O_3	1.71	14.57	24.3	23.05	1.31	1.59	2.72
CaO	43.76	29.71	33.40	33.11	46.5	45.5	66.3
MgO	0.9	3.19	3.83	3.78	1.08	1.3	1.95
LOI	36.00	-	-	-	38.7	1.00	0.9
CO_2	35.00	-	-	-	38.3	1.00	0
K_2O	0.53	0.55	0.74	0.67	0.7	10.19	0.61
Na_2O	0.14	1.42	2.35	2.31	0.56	7.76	0.68
SO_3	0.24	-	-	-	0.25	3.62	0.72
TiO_2	0.14	2.30	2.32	2.92	0.13	0.16	0.28
P_2O_5	0.07	0.70	0.00	0.19	0.06	0.07	0.11
Cl	0.02	-	-	-	0.28	8.24	0.13

With the information summarized in Table 3.II, the material balance was calculated. Concerning the fuels, only the ash content is considered in the material balance, because the combustible fractions are transformed into the gas phase and have therefore no effect on the material balance. The raw meal is added to the balance including moisture, total organic carbon (TOC) and sulphur. According to Table 3.III, the kiln feed to clinker ratio is 1.72.

Table 3.III: Material balance

Material Input	Mass flow [t/h]	Mass flow [kg/kg clinker]	Material Output	Mass flow [t/h]	Mass flow [kg/kg clinker]
Kiln feed, wet including TOC, S^{-2}	180.77	1.72	Clinker	105.06	1.00
Fuel ash	3.10	0.03	Preheater dust	22.30	0.21
Fuel SO_3	0.53	0.01	Bypass dust	1.00	0.01
Fuel Cl	0.10	0.00	SO_2 in preheater exit	0.09	0.00
-	-	-	Dehydration/ decarbonation	55.41	0.53
Σ	184.50	1.76	Σ	183.86	1.75

Accordingly, the theoretical energy needed for the chemical reactions was calculated. Based on 1.63 % crystal water per kg of clinker, the heat of clinker formation is composed of the heat of reaction stated in Table 3.IV. The difference between the endothermic heat of reaction, which is consumed, and the exothermic heat of reaction, which is released, results in the theoretical heat of formation of 1,701 kJ/kg clinker, which is in the range of the theoretical values in chapter 2.3.1. Most of the heat, namely 2,110 kJ/kg clinker, is consumed by the decarbonisation. This is the reason, why most of the energy has to be deployed at the precalciner.

Table 3.IV: Heat of clinker formation

Endothermic reactions [kJ/kg clinker]		Exothermic reactions [kJ/kg clinker]	
Clay dehydration	95.10	Clinkerisation	408.69
$CaCO_3$ decarbonisation	2,056.00	Alkalisulphates	95.30
$MgCO_3$ decarbonisation	54.00		
Σ	2,205.10	Σ	503.99
Theoretical heat of formation		1,701.11	kJ/kg clinker

The resulting clinker phases, calculated according to the Bogue matrix (see chapter 1.2.2), are listed in Table 3.V.

Table 3.V: Resulting clinker composition

Clinker Phases [%]	
C_3S	56.5
C_2S	18.5
C_3A	7.7
C_4AF	8.3
Free lime	4.1

3.1.4 Gas Flow

Besides material sampling, analysis and wall loss calculations, the scope of the audit was the measurement of gas velocities, temperatures, pressures and gas analyses in order to determine volume flow rates in the ductwork, heat transport and chemical composition for the creation of a gas balance. All entering and exiting gas flows are summarised in Table 3.VI.

The gas volumes entering at the kiln head and the cooler fans as well as all gas temperatures were inserted as measured during the audit. Exiting gases were back-calculated taking account of the waste gases of raw materials and fuels and the false air. The calculated values were verified by comparison with the measured values. False air results from leakages in the system and is either back-calculated or estimated by Lafarge. Air leakages leaving the system are not considered because of the constant negative pressure in the kiln and preheater tower, which is maintained by the preheater fan. 5.91 % of the kiln gas volume is bypassed, which amounts to 0.036 Nm^3/kg clinker or 3,818 Nm^3/h and contains 262 g/Nm^3 of dust.

Due to the combustion process and loss of ignition, the exhaust gas volume exceeds the entering air flux. This results in a difference of 39,003 Nm^3/h between in- and outflowing gas volumes. Regarding the air that is fed into the cooler by the cooler fans, 45,301 Nm^3 are entering the rotary kiln as secondary air at a temperature of 1068 °C and 49,738 Nm^3 are channelled to the precalciner as tertiary air at a temperature of 650 °C. The preheater exit gas is used to dry the raw materials in the raw mill, while the cooler exhaust gas is connected with the cement mill.

Table 3.VI: Gas balance

Entering gas	**Volume flow [Nm³/h]**	**Temperature [°C]**	**Exiting gas**	**Volume flow [Nm³/h]**	**Temperature [°C]**
Main burner			*Preheater*		
Primary air	6,150	54	Exit gas	171,922	346
Transport air # 1	1,800	56	*Cooler*		
Transport air # 2	1,350	50	Exhaust air	97,128	314
Precalciner			*Bypass*		
Transport air	1,725	30	Extracted gas	3,818	1,100
Cooler			-		
Fan # 1	19,752	27	-		
Fan # 2	47,290	21	-		
Fan # 3	47,064	23	-		
Fan # 4	28,531	20	-		
Fan # 5	16,192	19	-		
Fan # 6	15,054	19	-		
Fan # 7	16,284	17	-		
False air			-		
Cooler	2,000	10	-		
Kiln hood	1,689	35	-		
Kiln inlet sealing	950	30	-		
Preheater	17,034	30	-		
Tertiary air duct	8,000	30	-		
Precalciner	3,000	-	-		
Σ	233,865	-	Σ	272,868	-

Table 3.VII shows the back-calculated gas flow rates for neutral reactions at the precalciner and kiln as well as the preheater exit gas flux including decarbonation, H_2O, 3.8 % O_2 and 0.35 % CO dry at the preheater exit and excluding the bypassed gas volume.

Table 3.VII: Neutral and exit gas flow rates

Constituent	Neutral calciner [Nm³/h]	Neutral kiln [Nm³/h]	Exit gas [Nm³/h]
CO_2	10,278	7,175	44,207
H_2O	12,170	5,340	20,029
SO_2	32	15	32
N_2	50,565	33,091	101,999
O_2	-	-	5,838
CO	-	-	538
Σ	73,045	45,621	172,643

Table 3.VIII gives an overview over the flue gas composition after the preheater according to the waste gas calculation.

Table 3.VIII: Preheater exit gas composition

Constituent	Concentration	Unit
CO_2	25.61	%
H_2O	11.60	%
N_2	59.08	%
O_2	3.38	%
CO	0.31	%
SO_2	183	ppm

3.1.5 Wall Losses

To calculate the wall losses, consisting of heat transport through radiation and convection, the whole kiln system was divided into 158 surfaces, whose temperature was determined with a thermo-camera at defined measuring points. Furthermore, the wind speed was measured through anemometry. The wall temperature values of the rotary kiln were acquired from the kiln shell scanner and via manual measurement with a pyrometer. The surface areas were determined from construction plans. With the knowledge of the surface area, wind speed as well as surface and ambient temperature, the heat loss across the walls of the kiln system can be described using the following equations.

$$Q_{radiation} = \varepsilon\, \sigma\, A\, (T_1^4 - T_2^4) \qquad (3\text{-}1)$$

Equation (3-1) gives the heat that is radiated by a hot surface, whereby ε is the emission coefficient, σ is the Stefan-Boltzmann constant. A is the surface area and T_1 and T_2 are the surface temperature and the ambient temperature respectively. The Stefan-Boltzmann constant is defined as 5.67×10^{-8} W m^{-2} K^{-4} and the value of the emission coefficient was estimated to amount to 0.95 [31].

View factors, which are multiplied with the radiation loss calculated after equation (3-1), were used to account for interference between two parallel radiating surfaces. For parallel cyclones, a view factor of 0.9 was assumed, whereas parallel surfaces with less than 2 m clearance were defined to have an emissivity of 0 and as a consequence no radiation losses. The emissivity of all other surfaces was assumed to be 0.95.

$$Q_{convection} = h\, A\, (T_1 - T_2) \qquad (3\text{-}2)$$

Equation (3-2) gives the heat that is emitted from hot surfaces due to convection, h is the convection coefficient. A is the surface area, and T_1 and T_2 are, again, the surface and the ambient temperature. The value of the convection coefficient is dependent on the wind speed and calculated differently for natural or forced convection as well as turbulent or laminar flow [31].

Table 3.IX: Specific heat loss due to convection and radiation

Plant component	Convection losses [kJ/kg clinker]	Radiation losses [kJ/kg clinker]	Total losses [kJ/kg clinker]	Relative losses [%]
Preheater	15	31	46	12
Calciner and riser	24	36	60	16
Tertiary air duct	9	-3	6	2
Rotary kiln	108	123	231	62
Kiln Hood and settling chamber	11	12	23	6
Clinker Cooler	2	5	7	2

Table 3.IX summarises the outcome of the wall loss calculation. It shows the specific heat losses due to convection, radiation and in total. For a production volume of 2,550 t of clinker,

the total specific wall heat losses account for 373 kJ/kg clinker. The negative heat loss of the tertiary air duct is plausible due to the radiation of the parallel rotary kiln.

3.2 Online Measurements

Further data for the analysis of carbon monoxide, pressure and temperature variations were extracted from the plant's online measurement system. Historic data from May 2017 to February 2018 was considered to explain the fluctuating conditions of the precalciner and its surroundings with a focus on the last months. In order to give the kind reader a better understanding of the online data presented in chapter 4.2, the online measuring points for temperature, pressure and gas analysis are indicated in Figure 3.9.

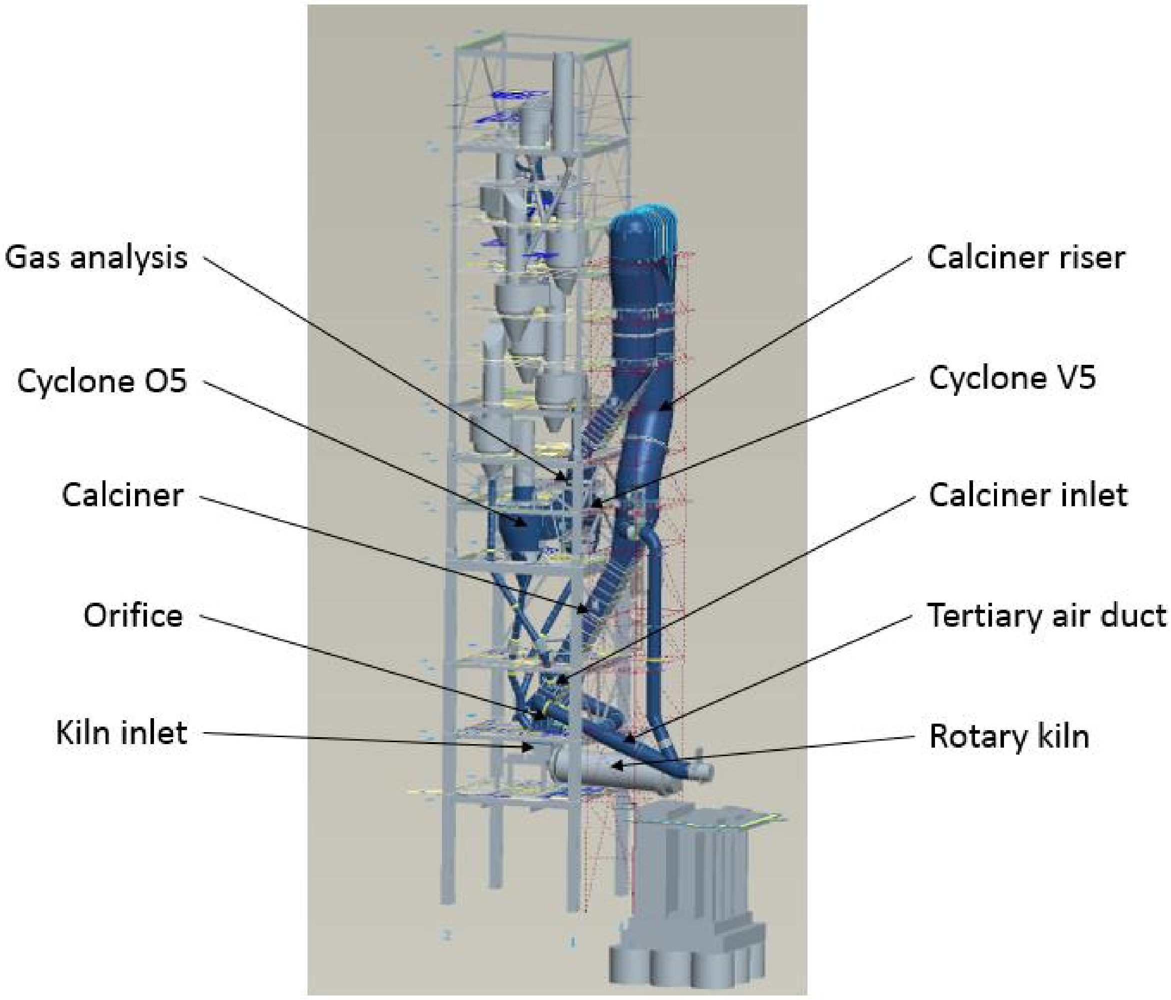

Figure 3.9: Measuring points in the preheater tower

The investigated properties were: gas content at the precalciner, preheater and chimney, temperature, pressure, mass flow and type of fuels at the main burner and the precalciner, mass flow of raw meal, alternative fuel rate, bunker filling levels, operation of the Kiln Master, air cannon activity and incidents in the daily report. The Kiln Master is a software for automatic kiln control, which is not always in operation. For some periods of time, e.g. critical situations, the automatic control is switched off and the process steered form by the control centre staff. Air cannons are used to remove deposit build-up in pipes and cyclones. The daily report is an additional source of information for a better understanding and correct interpretation of the measured values.

4 Analysis

With the data acquired during the audit and supported by the online measurements, energy balances of the whole system and of the individual components were calculated using MS Excel according to standards of LafargeHolcim. The analysis of the data was conducted with regard on the energy efficiency and process stability, and is the basis for the formulation of subsequent optimization measures.

4.1 Energy Efficiency

Based on the collected data, a heat balance of the entire pyroprocessing unit was created. The collected data serves as a basis for the evaluation of the energy consumption, the identification of weak spots and the derivation of potential for improvement.

4.1.1 Overall Heat Balance

Table 4.I and Table 4.II show the in- and output of specific enthalpy expressed in kJ/kg clinker. The difference of 72 kJ/kg clinker between the two total specific enthalpies, which accounts for 1.94 % of the total heat output, is an indicator for the quality and reliability of the heat balance. The enthalpy input of the fuels contains sensible heat, combustion heat, moisture, TOC and S^{-2}. The specific heat consumption (SHC) of 3,556 kJ/kg clinker lies within the range of values that were discussed in chapter 2.3.1, but is still elevated. For a precalciner kiln with a three to five stage suspension preheater, the SHC should account for 3,000 to 4,000 kJ/kg clinker, according to the literature.

Table 4.I: Kiln system heat input

	Mass flow [kg/h]	Temperature [°C]	Enthalpy [kJ/kg clinker]	Heat ratio [%]
Kiln feed	180,029	55.50	77.07	2.0
H_2O	362	55.50	0.80	0.0
Fuels	20,568	-	3,626.51	96.1
False air	35,647	30.00	10.39	0.3
Primary air	14,203	50.00	6.84	0.2
Cooler air	244,976	21.00	50.17	1.3
SNCR	102	20.00	0.08	0.0
Σ	-	-	3,771.86	-

Table 4.II: Kiln system heat output

	Mass flow [kg/h]	Temperature [°C]	Enthalpy [kJ/kg clinker]	Heat ratio [%]
Preheater exit gas	237,793	346	846.46	22.9
Carbon monoxide	669		64.33	1.7
Cooler exhaust air	125,122	314	383.61	10.4
Clinker	98,200	170	130.15	3.5
Tertiary air dust	2,980	800	21.87	0.6
Cooler exhaust dust	3,880	314	10.10	0.3
Clinker formation	-	-	1,701.12	46.0
Preheater dust	22,300	340	70.86	1.9
Bypass gas	5,140	1,100	63.52	1.7
Bypass dust	1,000	1,180	11.76	0.3
Bypass decarbonisation		-	13.30	0.4
SNCR	61	-	1.45	0.0
Moisture kiln feed	362	-	8.56	0.2
Wall losses	-	-	373.00	10.1
Σ	-	-	3,700.09	-

In the case of Mannersdorf, a kiln system with the mentioned equipment and a five stage preheater is installed, however, some of the equipment, especially the existing preheater and clinker cooler are comparatively old.

H_2O refers to the water that is introduced into the system due to the moisture of the raw meal. False air is the sum of inleaking air throughout the process. Primary air consists of the primary air of the main burner and the transport air of the main burner and precalciner. Cooler air represents the volume flow through the cooler fans. Finally, the mass and enthalpy flow of the injected urea is taken into account.

Enthalpy flows exiting the system are the preheater exit gas, cooler exhaust air and bypass gas. Further losses are the sensible heat of clinker and dusts as well as wall losses. Reaction heat has to be applied for the evaporation of injected water urea, and kiln feed moisture, the decarbonisation of bypass dust and clinker formation, which is referred to as formation heat. Finally, the emission of carbon monoxide that is generated throughout the process has to be taken into account.

Overlooking the kiln balance, the losses due to carbon monoxide emissions and its high calorific value are significant. Furthermore, the high volume and temperature of preheater exit gas, cooler exhaust gas and bypass gas, and the sensible heat of the clinker are conspicuous. The preheater exit gas is, in case of raw mill operation, used to dry the raw meal, which saves heat consumption at the subsequent processes, while the bypass gas is quenched, filtered and released at the chimney. A part of the cooler exhaust air is used in the cement mills, but since its volumes are very high, there is still room for further application. A mixture of flue gas before the chimney and preheater gas after the SCR is applied at the coal mill. The clinker temperature is dependent on the cooler efficiency, which could be improved considering the clinker temperature of 170 °C after the cooler. Wall losses are a consequence of large surfaces and hot wall temperatures and can be minimized with appropriate insulation. The most important part, consuming 46 % of total heat, is the clinker formation. Its heat consumption is given by the heat of reaction of the individual conversion stages like decarbonation and sintering.

4.1.2 Preheater

In terms of wall losses, the installations in the preheater tower which consist of ductwork and cyclones have an advantage because they are encased to a great extent. Moreover, the two preheater lines irradiate each other and thereby decrease their radiation losses. The heat losses account for 46 kJ/kg clinker but occur at a low temperature level, so that heat recovery is not appropriate. A way to avoid them, is to intensify the insulation of cyclones and ductwork. An important issue is the high volume of false air that enters the preheater installation. The calculated inleaking volume flow rate of 14,034 Nm³/h account for 8.1 % of the total preheater exit gas. High false air volumes deteriorate the energy efficiency, because of diluted flue gas volumes. On the one hand, the flue gas volumes that have to be channelled through the system are higher and on the other hand, the fuel consumption increases to maintain the temperature niveau in the preheater. The same is true for the preheater oxygen concentration, which amounts to an average level of 3.4 % wet and cannot be decreased because of the stability problems that are covered in chapter 4.2. Finally, the poor top cyclone efficiency of 88 % has to be mentioned. Its effect on the energy efficiency is that high amounts of dried and hot raw meal is lost to the filter, from where it has to be recovered and recycled into the system. The preheater dust has a mass flow of 22,300 kg/h, an enthalpy flow of 70.86 kJ/kg clinker and accounts for 1.9 % of the total heat output. The dust affects the energy efficiency, because the sensible heat of the raw meal that leaves the kiln system is lost to a great extent.

4.1.3 Precalciner

Due to its higher operation and surface temperature, the wall losses are higher for the precalciner than for the preheater, amounting to 60 kJ/kg clinker, but the temperature levels are still not suitable for efficient heat recovery. Furthermore, the reactions taking place on the inside must not be disturbed by lower wall temperatures. Consuming 58 % of the SHC, the precalciner reaches a calcination degree of 90.8 % with temporary alternative fuel rates (AFR) of 100 %. Its false air volume is much lower than that of the preheater and estimated to account for 3,000 Nm³/h or 1.7 % of total preheater exit gas. Critical issues concerning the internal processes of the precalciner, such as a blocked up tertiary air duct and problems regarding fuel dosing, are discussed in chapter 4.2.

4.1.4 Rotary Kiln

61 % of the wall heat losses are caused by the rotary kiln, which has also the highest wall temperatures with values between 116 °C and 374 °C, and an average wall temperature of 276 °C. Additionally, it was subjected to high wind velocities of around 5 m/s during the audit, which effect enforced convection. Heat recovery is complicated because of the rotary movement of the kiln and disturbances of the internal reactions. A technically viable solution to insulate the kiln or recover the heat from its shell has not been found yet. The burner of the rotary kiln consumes 42 % of the SHC (including fall through) by combustion of high calorific

fuels including 1.5 to 4.8 t/h of petroleum coke, which is responsible for the share of conventional fuels. The kiln itself generates a false air volume of 2,639 Nm³/h that originate from the kiln hood and kiln inlet sealing, while the tertiary air duct and settlement chamber generate 8,000 Nm³/h of false air.

4.1.5 Clinker Cooler

Table 4.III and **Table 4.IV** show the heat balance of the grate cooler.

Table 4.III: Clinker cooler heat input

	Mass flow [kg/h]	**Temperature [°C]**	**Enthalpy [kJ/kg clinker]**	**Heat ratio [%]**
Cooling fans	244,976	21	50.17	3.0
Hot clinker	105,060	1,430	1,579.56	93.7
False air	2,576	10	0.25	0.0
Clinker Dust return (SA)	2,714	1,430	40.81	2.4
Clinker Dust return (TA)	993	1,430	14.94	0.9
Σ	356,319	-	1,685.73	-

Table 4.IV: Clinker cooler heat output

	Mass flow [kg/h]	**Temperature [°C]**	**Heat [kJ/kg clinker]**	**Heat ratio [%]**
Secondary air	58,357	1,068	654.96	38.9
Tertiary air	64,073	650	420.59	25.0
Exhaust air	125,122	314	383.61	22.8
Cold clinker	98,200	170	130.15	7.7
Wall losses	-	-	30.00	1.8
Dust secondary air	2,714	1,050	27.15	1.6
Dust tertiary air	3,974	800	29.16	1.7
Dust exhaust air	3,880	314	10.10	0.6
Air leakage	0	25	0.00	0.0
Σ	356,320	-	1,685.72	-

Cooling air, hot clinker coming from the rotary kiln, false air and the dust returning from the secondary and tertiary air form the inbound enthalpy streams. Seven fans provide 190,167 Nm³/h of cooling air at an average temperature of 21 °C.

Wall losses amount to 30 kJ/kg clinker and are small compared to the high temperatures and mass flows of leaving and entering gases and clinker, but in the cooler heat balance, they are responsible of 1.8 % of the heat output. Secondary, tertiary and exhaust air are leaving the clinker cooler at high volume flow rates and temperatures. Therefore, they account for 86.5 % of all outbound enthalpy flows. The remaining heat is lost through the walls or absorbed by the dust. Finally, some cooling air is leaking at the bottom side of the cooler. Coming from the rotary kiln, the clinker is cooled from 1430 °C to 170 °C at a recovery efficiency of 66.8 %. The heat losses of the cooler, including the exhaust gas, are summed up to 554 kJ/kg clinker, which is a considerable proportion of the total heat input.

As already mentioned in chapter 4.1.1, the enthalpy of the cooler exhaust gas as well as its volume and temperature level is suitable for a wide range of further applications such as waste heat recovery or drying of fuels and raw materials. The fact that the clinker temperature is still very high after the cooler raises the question, whether the cooling efficiency can be increased or the heat can be extracted in other ways. However, a dryer for main burner fuels is already in the planning stage. Another critical point is the low tertiary air temperature that is even declined on its way through the settlement chamber. Finally, the tertiary air enters the precalciner at an average temperature of 507 °C, according to the online measurements during the audit.

4.2 Process Stability

Together with the installation of the new precalciner, higher alternative fuel rates and the burning of coarse low quality fuel at the precalciner, a number of process stability problems manifested in the daily operation. These include pressure and temperature fluctuations as well as CO-peaks. In order to implement energy efficiency measures like reducing the air-fuel ratio at the kiln or the temperature level at the precalciner or by any means exploiting the system limitations, those instabilities have to be kept under control. The analysis of the online data produced the following results.

4.2.1 Carbon Monoxide Formation

The problem concerning carbon monoxide emissions is distinctly visible in the following diagram. Figure 4.1 shows the CO concentration at the precalciner and the chimney on from January 7th, 6 am to January 8th, 6 am. Apart from a certain ground level of CO concentrations of around 0.2 % and 1000 mg /Nm³, concentration peaks at the precalciner followed by emission peaks at the chimney, which often exceed 1 % or 3000 mg /Nm³, dominate the graph. During that timeframe, the average CO concentration is 0.06 % leading to emissions of 909 mg/Nm³ at the chimney. The daily report does not contain any incidents regarding the fuel feeding system.

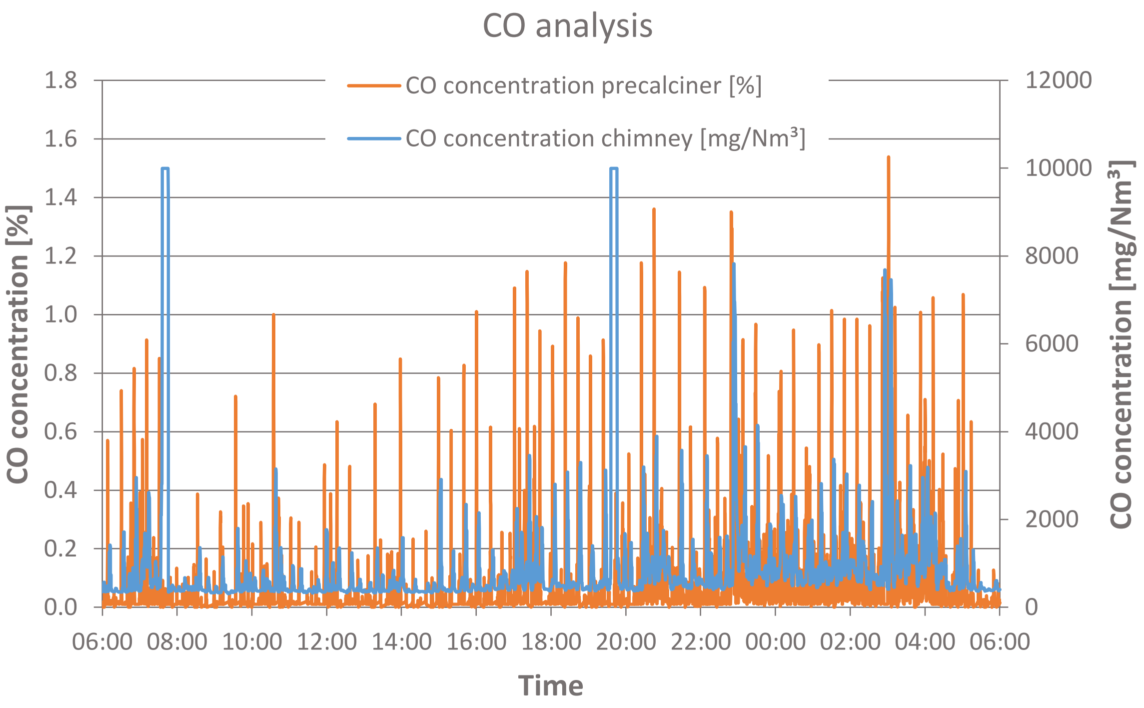

Figure 4.1: CO concentration at the precalciner and the chimney

Carbon monoxide formation is the result of incomplete combustion. When there is not enough oxygen in the combustion air, the carbon is oxidized only partly, whereby the flue gas contains carbon monoxide instead of the fully oxidized carbon dioxide. As shown in Figure 4.2, which is a section of Figure 4.1 and was recorded on January 8th between 1 am and 3 am, a carbon monoxide peak is accompanied by an oxygen valley. In this case, the critical factor is not the oxygen concentration itself, because the gas composition coming from the kiln is quite stable and the oxygen minima are occurring after the carbon monoxide peaks. Determining factors seem to be the either the quality or the quantity of precalciner fuels.

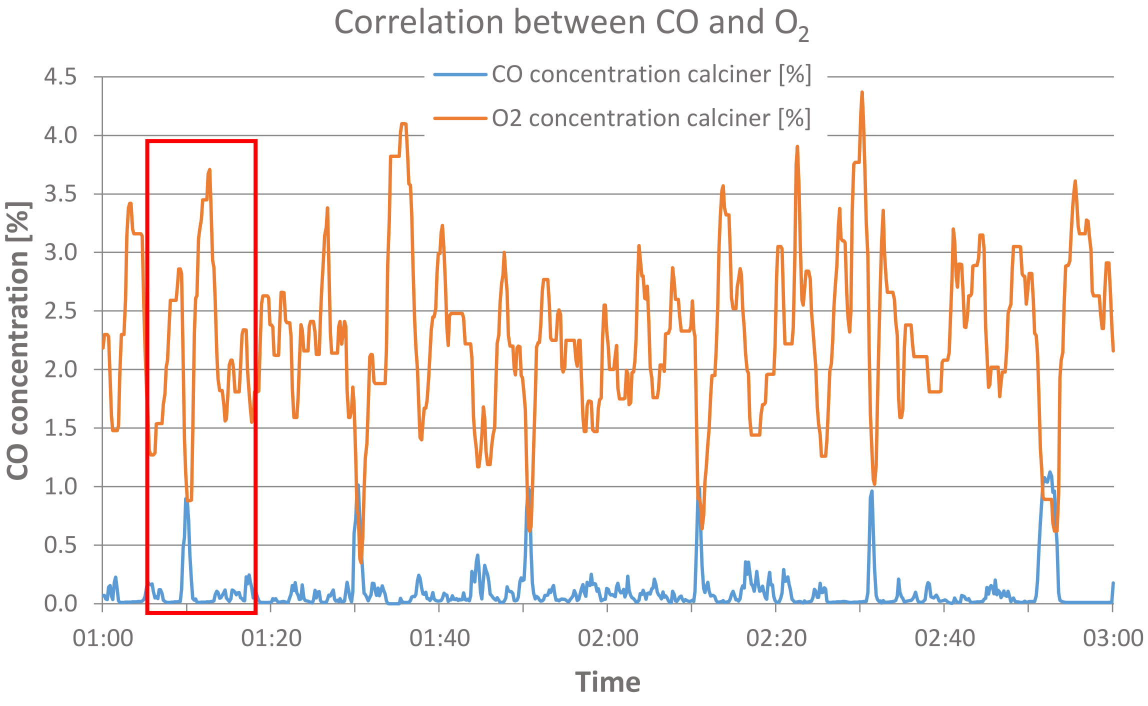

Figure 4.2: CO and O_2 concentration measured at the precalciner

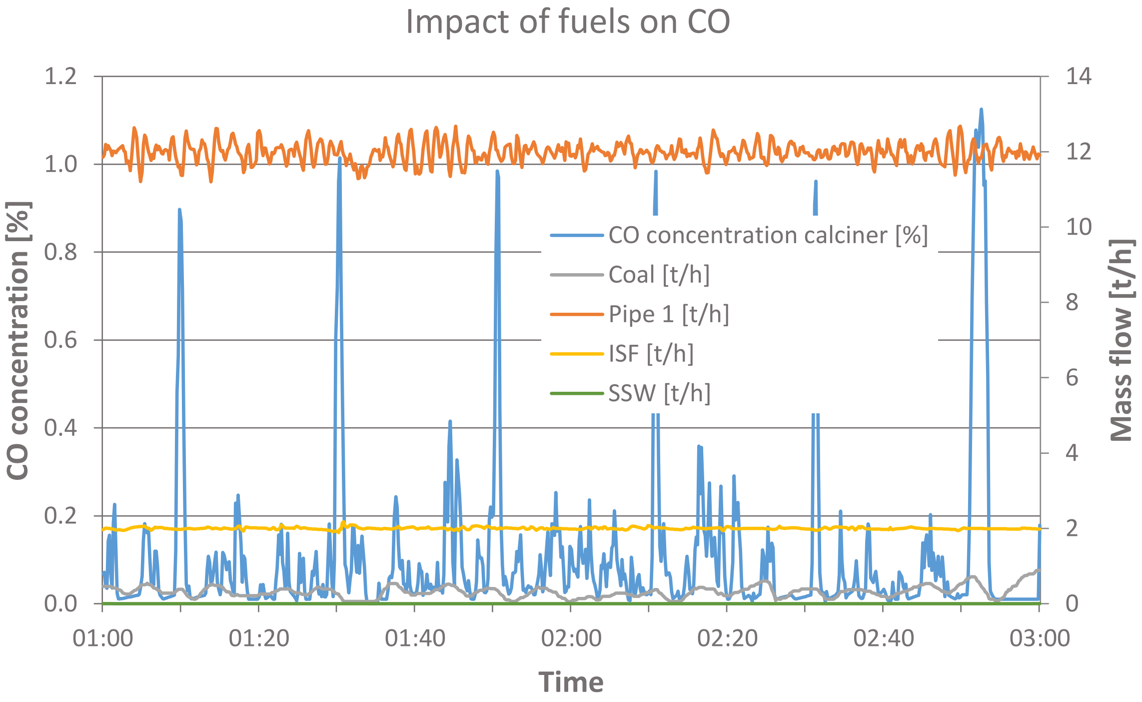

Figure 4.3: CO concentration and fuel mass flow measured at the precalciner

Figure 4.3 shows the fuel feed rate for the same time window as Figure 4.2, in which the precalciner was supplied with petroleum coke (Coal), ASB (Pipe 1) and ISF. While ISF was fed in a relatively stable manner, Pipe 1 shows variations of about 1.2 t/h, Petroleum coke was fed in batches and the SSW supply was not in operation at that time. The small CO concentration peaks follow the petroleum coke upsurges, but the sudden CO maxima that occur exactly with an interval of 20 minutes do not correlate with the online-measured fuel supply.

An online-measured parameter that correlates with the mentioned interval is the filling level of the coal bunker, which is depicted in Figure 4.4. This bunker is located in the preheater tower and serves as a temporary storage for coal and petroleum coke coming from the coal mill. A subsequent scale is responsible for the dosing of the coal or petroleum coke before it is fed into the precalciner. Further investigation will be necessary to detect the exact source of error.

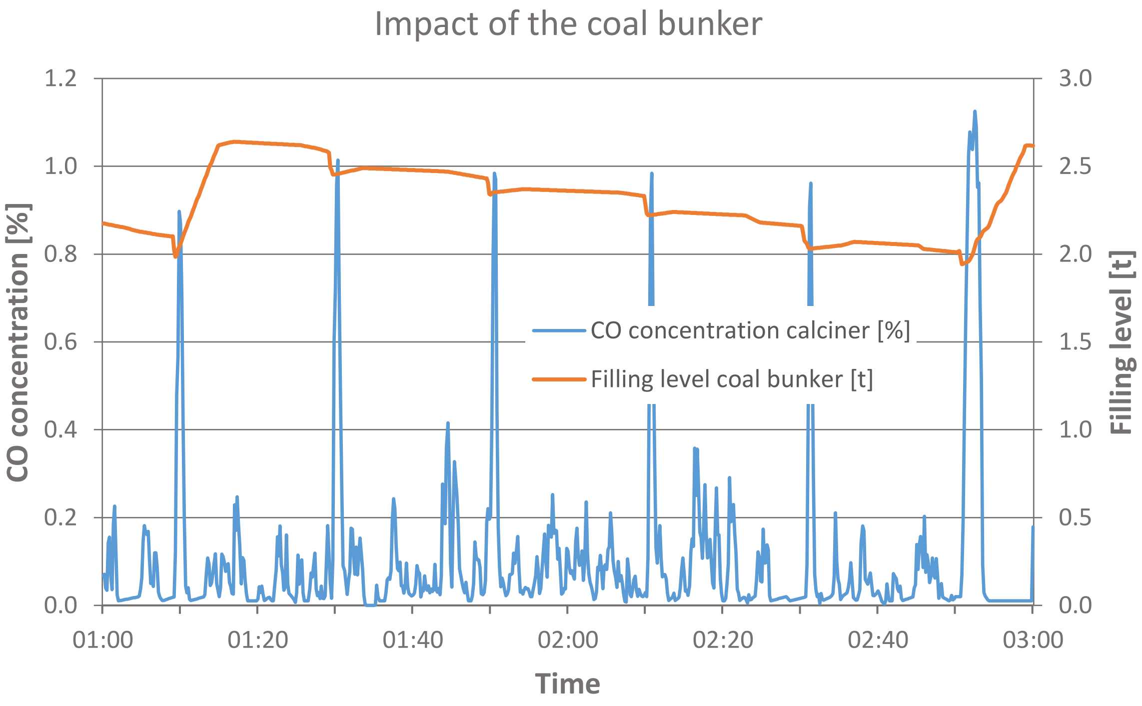

Figure 4.4: CO concentration and filling level of the coal bunker

From an environmental point of view, the peaks are not yet a big problem, because, as stated in chapter 2.1.2, there are no emission limits for carbon monoxide and the peaks are smoothened when calculating the half-hourly average. However, regarding the energy efficiency, a number of issues arise. Firstly, the oxygen concentration at the precalciner inlet has to be elevated to allow reasonably effective combustion of fuels. To increase the oxygen level, more combustion air needs to be provided. The negative effects on the energy efficiency are the additional electricity consumption by the fans that deliver the combustion air, higher flue gas volumes, a high air ratio in the rotary kiln and higher heat consumption. The latter is a consequence of the fact that nitrogen, which is the most abundant element in the ambient air, does not participate in the combustion reaction but absorbs heat. Secondly, carbon monoxide has a high calorific value that is actually leaving the system through the chimney. The losses due to the unused enthalpy amounts to 64 kJ/kg clinker, which is 1.7 % of the total thermal heat consumption.

4.2.2 Pressure Instability

Further instabilities in the processing system are strong pressure variations as illustrated in Figure 4.5. They occur quite often but irregularly and are characterised by a pressure drop in the precalciner and rising pipes of the bottom cyclones O5 and V5. The values depicted in the following diagram were measured on the January 4th 2018. It was found that there are different kinds of pressure variation, dependent on their origin. In some cases the kiln inlet pressure, which is measured right beneath the orifice, decreases and in others, it increases. A drop of the kiln inlet pressure together with all other pressures throughout the preheater tower happens when the flow area increases. This is the case, when there are less particles in the gas ducts of the precalciner. At stable raw meal feed rates, the pressure drop can be correlated with a fuel deficiency at the precalciner.

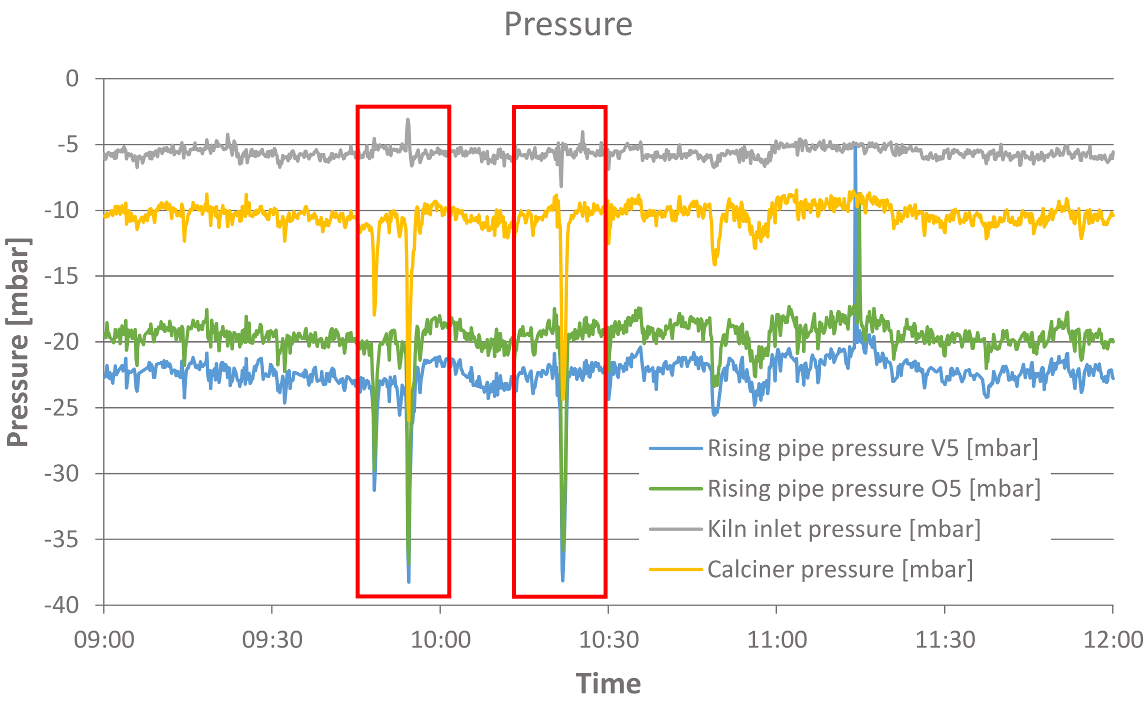

Figure 4.5: Pressure fluctuations, January 4th 2018

This first kind of pressure variations can be clearly referred to a fuel change, which is shown in Figure 4.6. In this case the alternative fuel rate at the precalciner falls from 12.5 t to 0 t in a few seconds at a fuel feed rate of 12.4 t/h leading to a pressure drop in the whole system. The pressure is stabilised after the start-up of the coal feeding system. According to the daily shift report, the pipe conveyor was switched off for control and repair work.

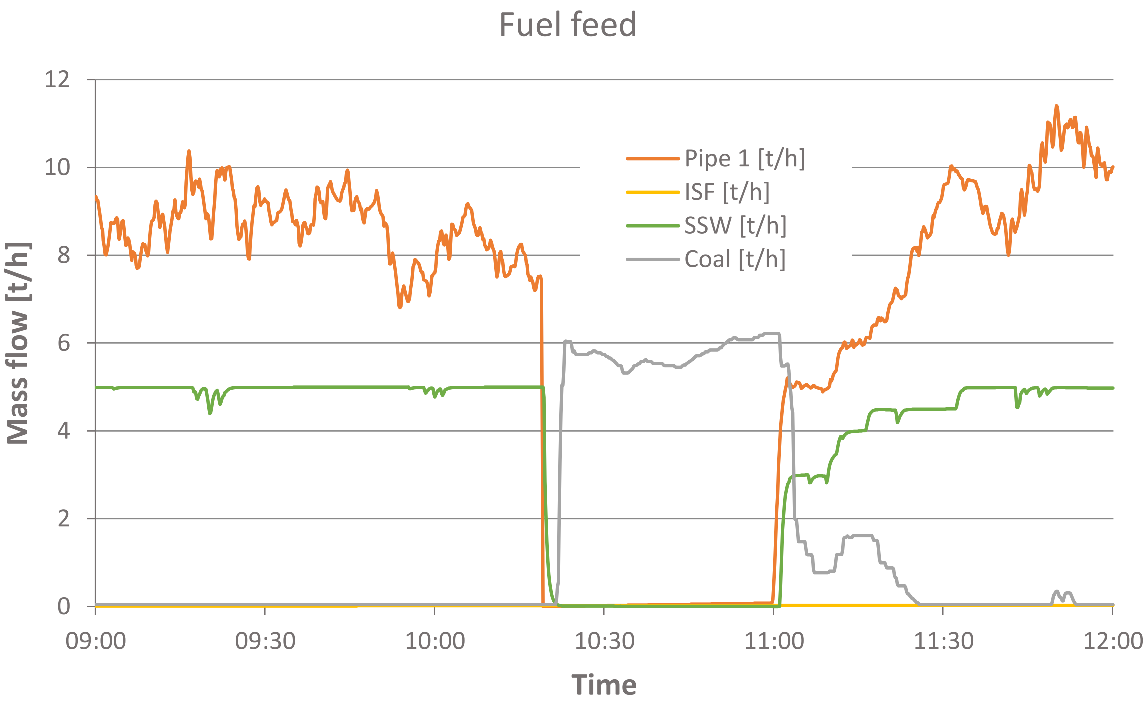

Figure 4.6: Fuel change, January 4th 2018

An increase of the kiln inlet pressure indicates that material is plugging the orifice. At the same time the preheater fan, which generates the negative pressure in the preheater, precalciner and kiln, is still working under nominal load and creates a pressure drop that cannot be compensated by the tertiary air duct.

Finally, the positive pressure disturbance that is included in Figure 4.5, is due to a cleaning operation executed by the plant personnel on a regular basis and is therefore not a process instability. The impact of air cannons on pressure variations has been investigated, but because the trigger times of all cannons are evenly distributed within equal intervals, no correlation could be found. In any case, the obstruction of one of the two tertiary air inlets at the precalciner, contributes to the difficulties regarding pressure fluctuations. However, the assumptions that are made in this chapter are difficult to prove, because it is not possible to look into the preheater, precalciner or kiln while they are operating.

It has to be noted that most of the fuel deficiencies entail not only a severe pressure drop throughout the preheater tower but also a significant increase of the CO concentration after the precalciner and at the chimney. This is due to the fact the Kiln Master is reacting very fast and start-up phases for fuels are executed within a few seconds as shown in Figure 4.7.

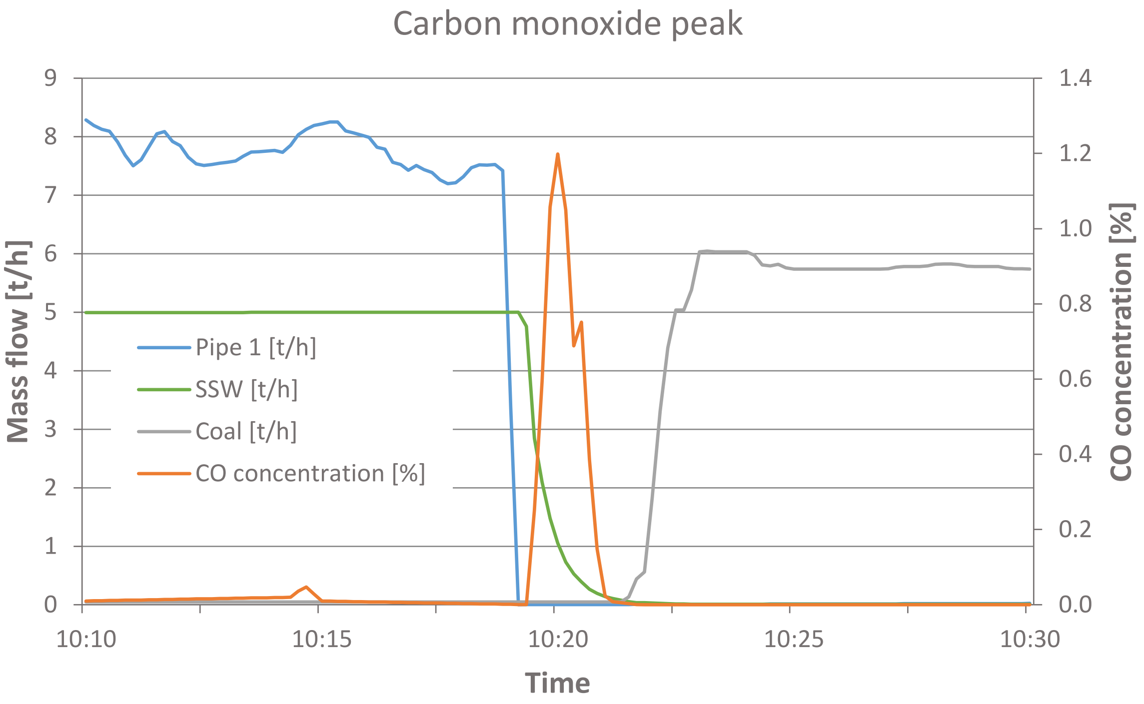

Figure 4.7: Fuel change and following CO peak

4.2.3 Temperature Instability

The third kind of instabilities that have been observed are temperature variations. As indicated in chapter 1.2.2, the ideal temperatures for a precalciner lie at around 900 °C and should be high enough to allow decarbonation but reasonably low to avoid deposit build-up by alkalis and decrease heat consumption. Actually, the temperature has to be kept relatively high due to the fluctuations shown in Figure 4.8, which represents the temperature behaviour at the riser, bottom cyclone and tertiary air duct outlet on January 4th and 5th 2018. The red lines tag the overall linear temperature trends and indicate the deviations from the ideal situation.

The average temperatures amount to 797 °C at the riser, 870 °C at cyclone O5 and 553 °C at the tertiary air outlet. While the deviation between the highest and the lowest measured temperature at the precalciner riser accounts for 83 °C, it accounts for 117 °C at the cyclone and 152 °C at the tertiary air outlet (TA outlet). Due to these fluctuations, there is no room for optimization of the default temperature.

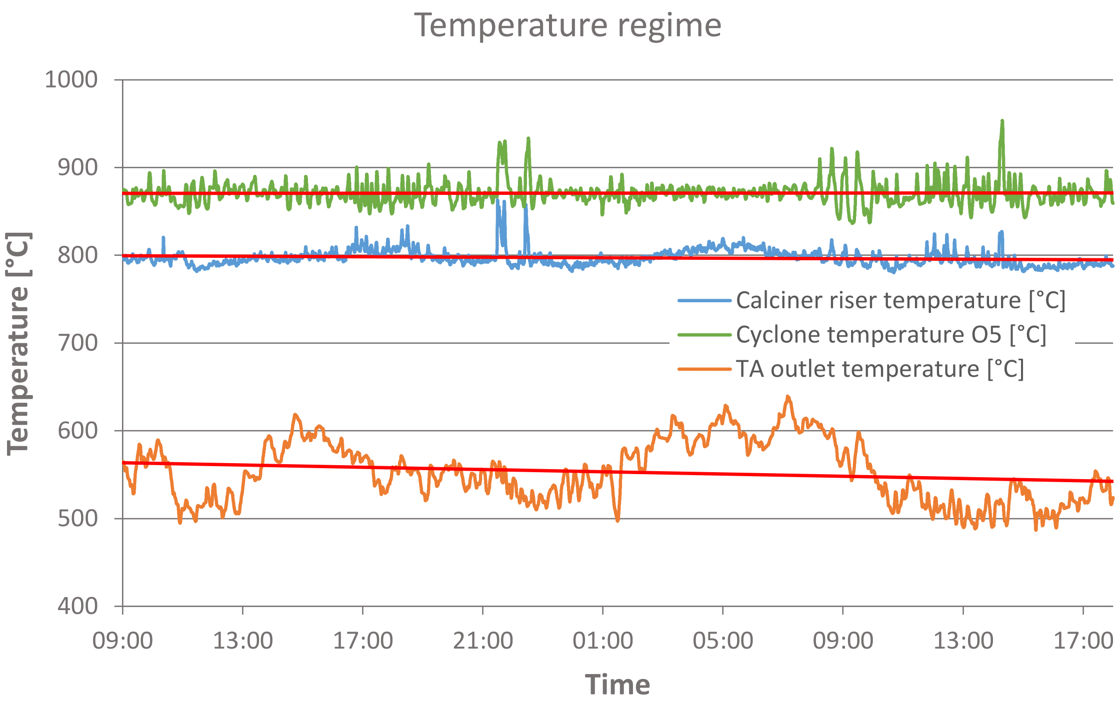

Figure 4.8: Temperature instabilities

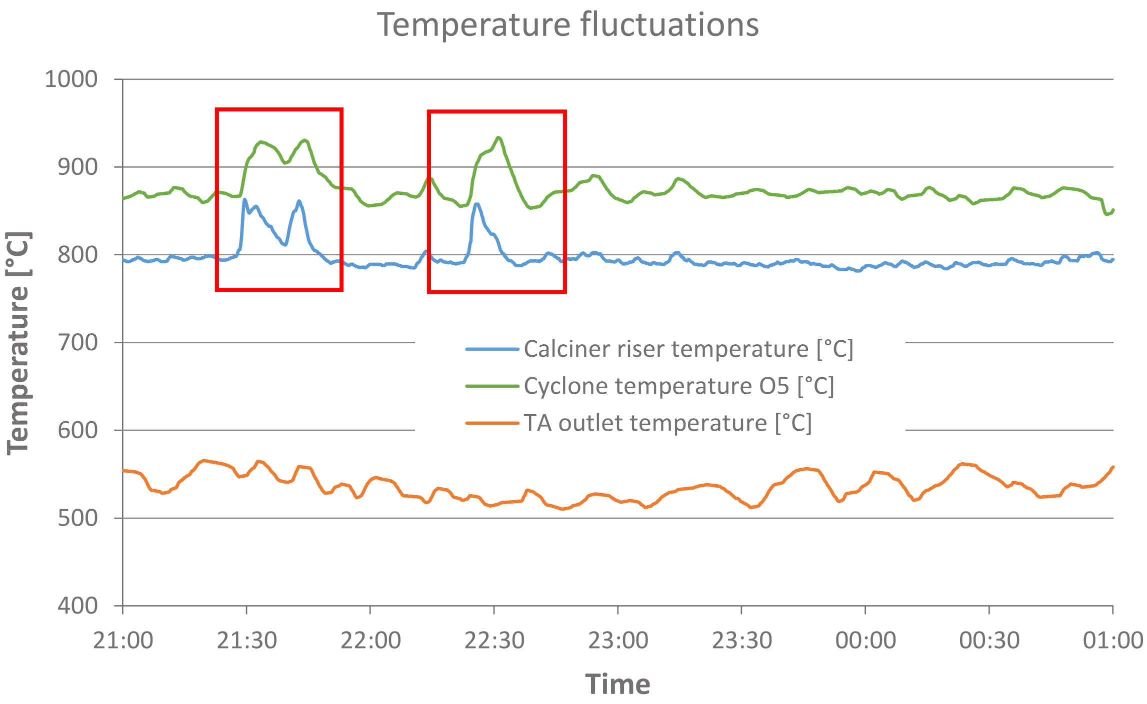

Figure 4.9: Temperature regime, January 4th 2018

Figure 4.9 and Figure 4.10 show the correlation between the temperature disturbances and the fuel feed. The daily report confirms that there were problems at the pipe conveyor, because of material agglomerations. An unsteady feed of different fuels leads to an irregular temperature distribution with significant variations.

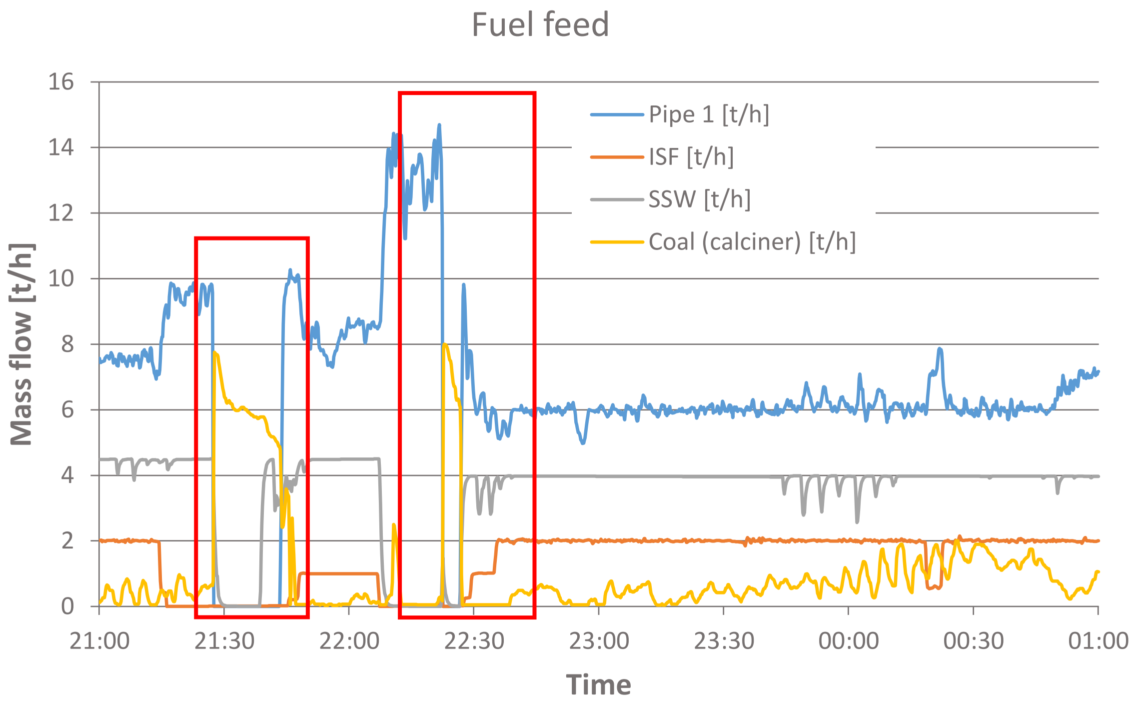

Figure 4.10: Fuel feed rates, January 4th 2018

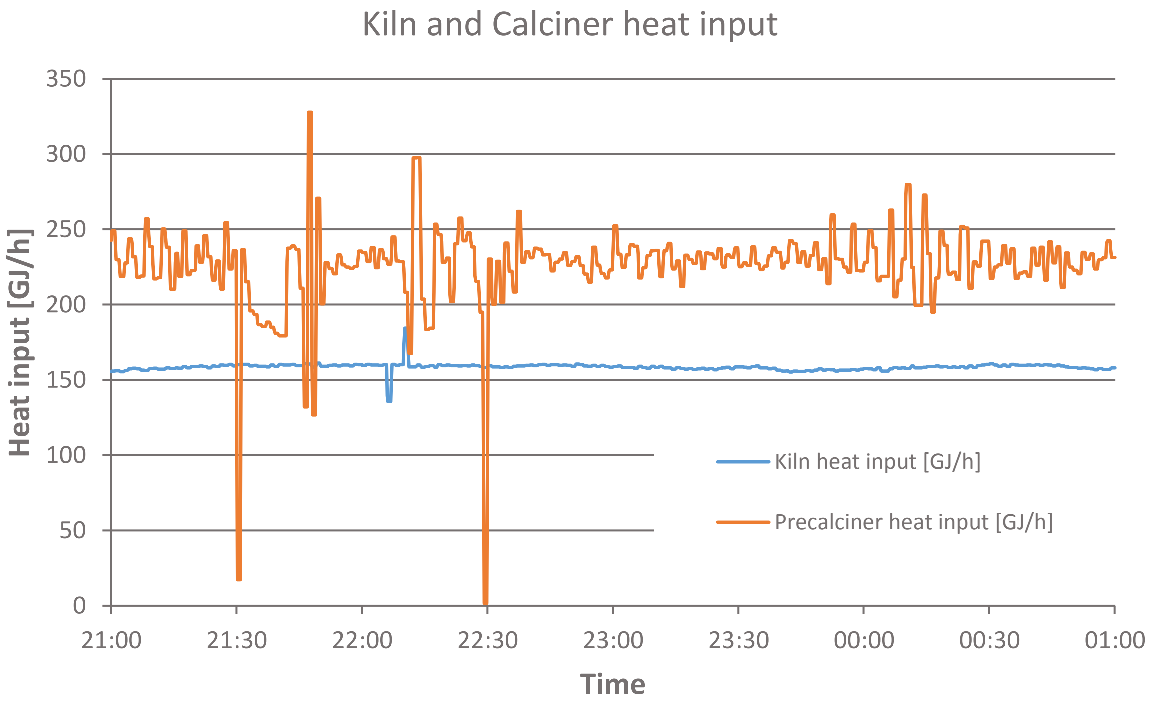

Figure 4.11: Heat input at the main burner and the precalciner

This effect is reinforced by the fact that the deployed fuels have different calorific values ranging from 17 kJ/kg to 43 kJ/kg, which are not even consistent for one fuel sort, especially regarding waste derived fuels. The fluctuating heat input at the precalciner, which is automatically back-calculated by the online-measurement system, is visible in Figure 4.11.

4.3 Comparison: Low Alternative Fuel Rate

The effects described in chapter 4.2 are mostly attenuated in phases with low alternative rates. Such a timeframe occurred on July 21st 2017 and is shown in Figure 4.12. The Kiln Master was deactivated at 2:25 am due to increasing CO concentrations and a SCR deficiency. Additionally, the pipe conveyor (Pipe 1) was deactivated after multiple malfunctions. These occurrences resulted in a high share of conventional fuels at the precalciner.

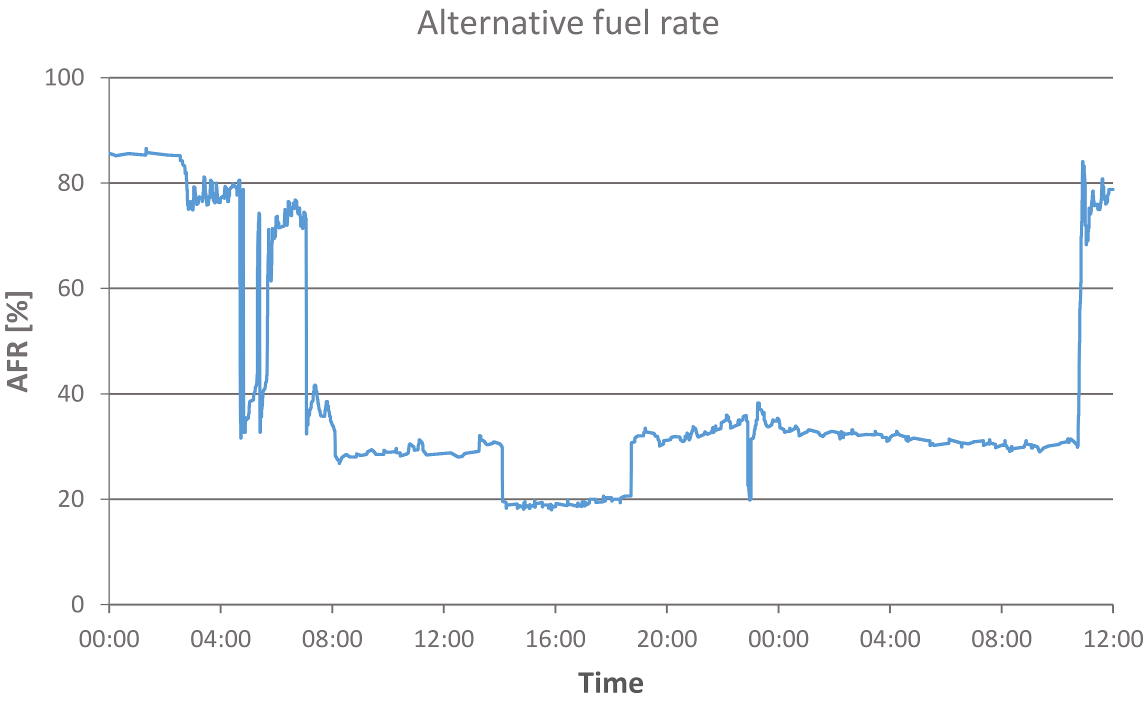

Figure 4.12: Alternative fuel rate, July 21st 2017

The raw meal feed was constant at an average value of 178 t/h, the fuel supply for Pipe 1, ISF, and SSW was shut off. Thus, the precalciner was operated with petroleum coke only, while the main burner fuels were injected at relatively stable rates, as shown in Figure 4.13. Still, the fuel flow at the main burner is much more uniform than at the precalciner, resulting from different feeding systems. Only the HCF feed became inoperative for a few hours. The chosen time interval is characterized by not only stable fuel and raw material feed rates but also by low CO concentrations after the precalciner, and relatively stable temperatures compared to periods with a high AFR.

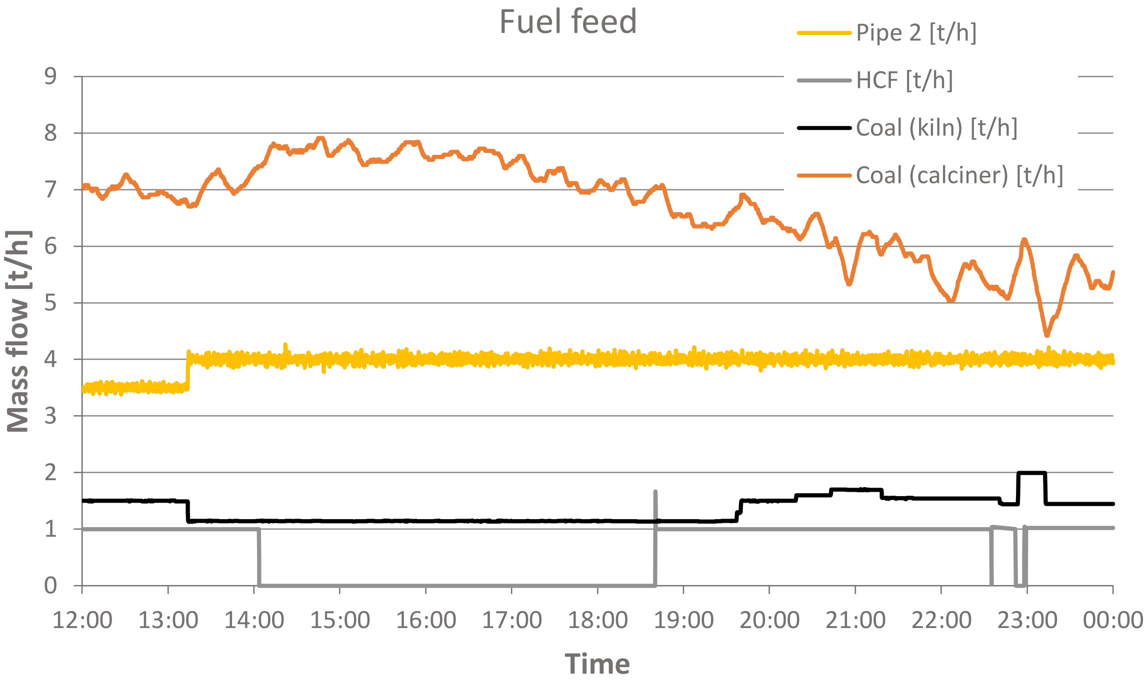

Figure 4.13: Fuel feed, July 21st 2017

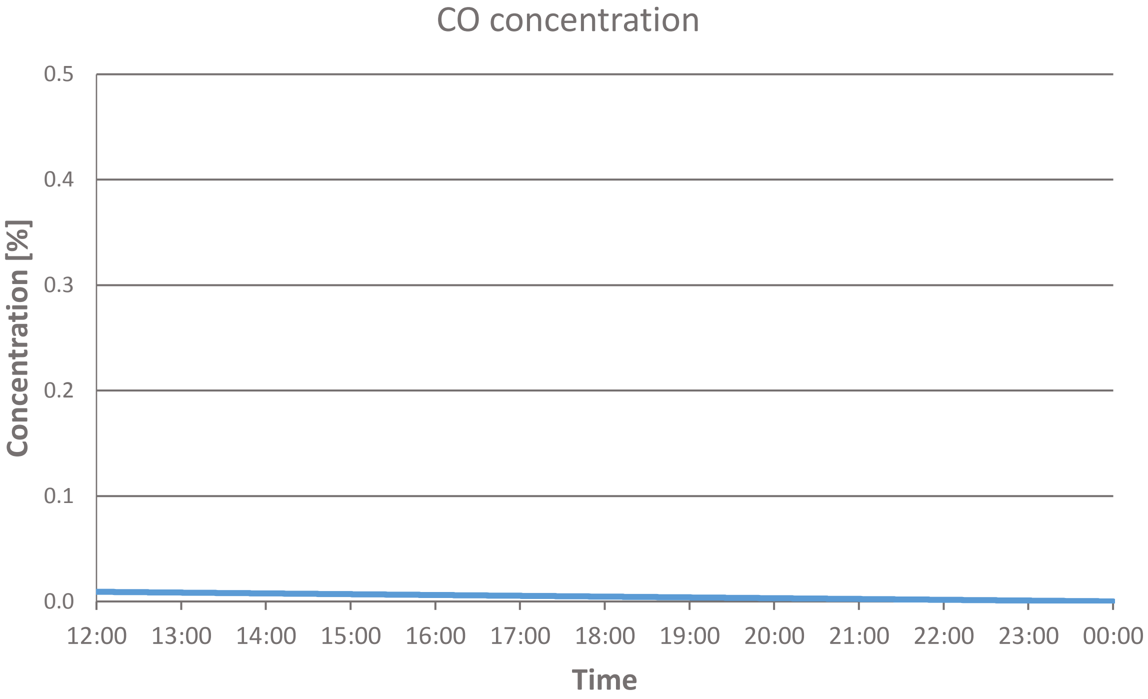

Figure 4.14: CO concentration, July 21st 2017

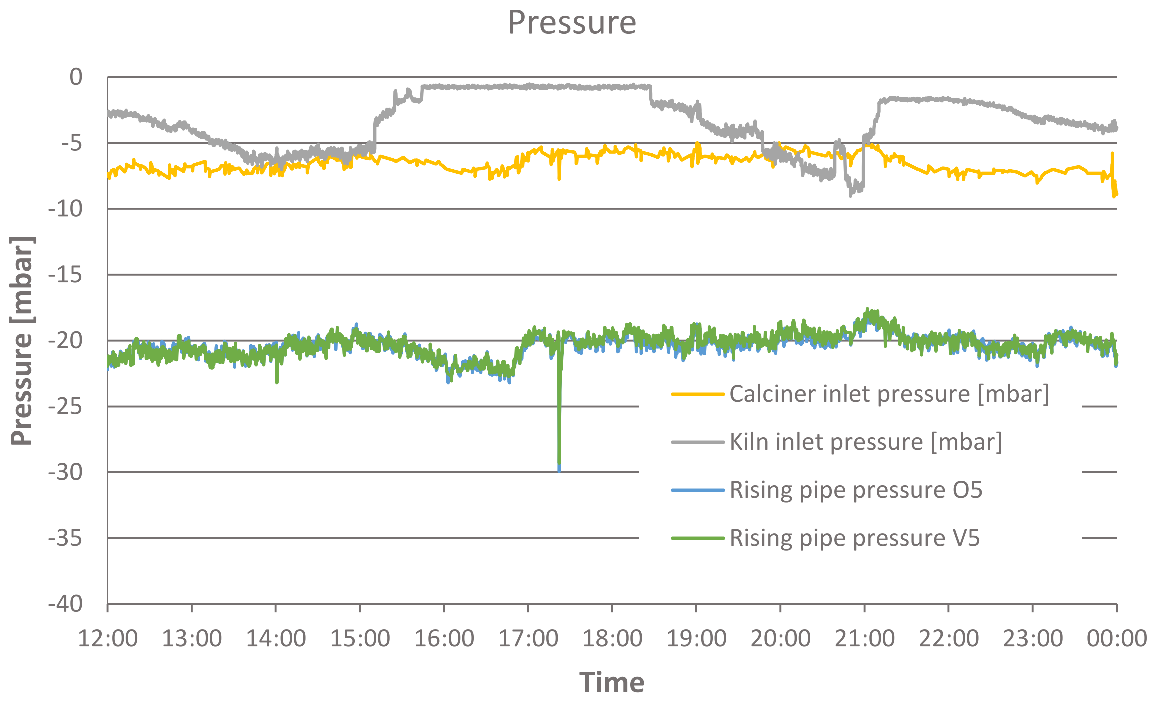

Figure 4.15: Pressure behaviour, July 21st 2017

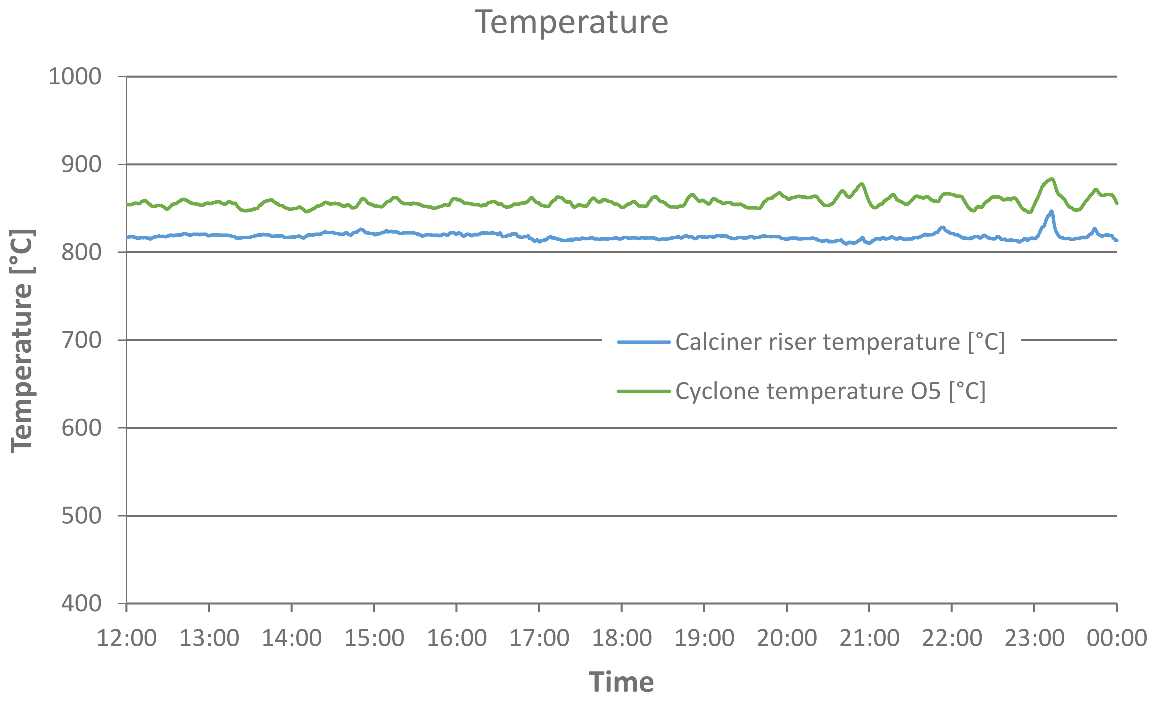

Figure 4.16: Temperature regime, July 21st 2017

There are still pressure disturbances, which are most clearly at the kiln inlet, but not as extreme as those in Figure 4.5. The behaviour of CO concentration, pressure and temperature are illustrated in Figure 4.14, Figure 4.15 and Figure 4.16. An assertion of the comparison of periods with low and high AFR is that the pressure and temperature fluctuations are clearly a consequence of the fuel feed at the precalciner, but is not dependent on the overall AFR. The positive impact of low alternative fuel rates is that the CO peaks are not present and that the variations of pressure and temperature are not as significant as in case of high AFR. Nevertheless, the coal injection at the precalciner happens in very uneven manner.

4.4 Comparison: Kiln Audit 2012

The preceding kiln audit in Mannersdorf was carried out in June 2012 in order to evaluate the heat and material flows, clinker cooler condition, SCR efficiency, emissions and combustion behaviour of the precalciner. Increasing alternative fuel rates while maintaining product quality and CO concentration after the precalciner was already a main topic back then, according to the audit report. However, it is difficult to compare the situation at that time with the present due to the major modifications accomplished in recent times. Especially the layout of the precalciner that was implemented in 2017 changed drastically. Figure 4.17 illustrates the flow sheet of the pyroprocessing unit as installed at the time of the kiln audit 2012.

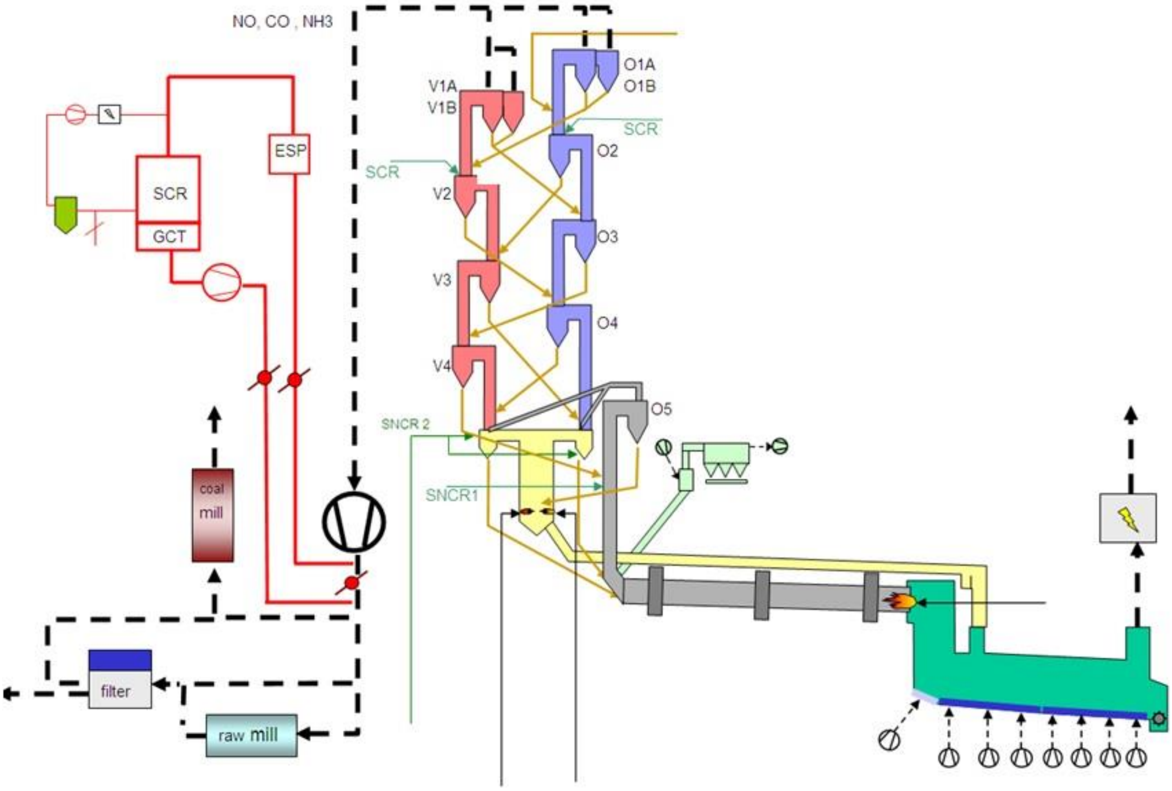

Figure 4.17: Flowsheet of the pyroprocessing unit in 2012

A remarkably great difference compared with Figure 3.1, which shows the flow scheme in 2017, is the missing gooseneck and the fuel feeding system at the precalciner. Furthermore, the configuration of cyclones was changed.

Instead of contrasting the measured values, it is more practical to compare the results of the material and energy balances from 2012 and 2017. Table 4.V and Table 4.VI give an overview over the audit results of the actual audit and the one from 2012.

Table 4.V: Audit results for preheater, precalciner and rotary kiln

Main parameter	Unit	2017	2012
Clinker production	[t/d]	2,521	2,335
Clinkerisation factor	[-]	1.72	1.82
Preheater exit dust	[g/Nm³]	129	171
Top cyclone efficiency	[%]	87,66	84,61
Specific heat consumption	[kJ/kg clinker]	3,555	3,597
Heat input on main burner	[%]	40,13	38,4
AFR	[%]	79.61	73.22
Thermal load (burning zone)	[MW/m²]	4.18	3.75
Specific preheater gas flow	[Nm³/kg clinker]	1.64	1.63
Specific preheater gas flow	[Am³/kg clinker]	4.32	4.02
Preheater exit gas oxygen, wet	[%]	3.38	3.5
False air preheater and precalciner	[%]	9.91	8.2
Preheater exit gas temperature	[°C]	346	311
Calcination degree	[%]	90.78	96.38
Kiln residence time	[min.]	25.82	26
CO2 total	[kg/kg clinker]	0.84	0.83
CO2 fossil total	[kg/kg clinker]	0.77	0.77
Net calorific value (main burner)	[kJ/kg]	24,064	25,132
Kiln loading	[%]	5.41	5.06

In 2012, the old equipment limited the clinker production to 2,335 t/day and the AFR to 73 %. The proportion of heat that was supplied by the main burner as well as the preheater gas temperature was lower and the top cyclone efficiency was poor, leading to more dust at the preheater exit. Since then, the clinker production increased for 7.4 %, the SHC dropped by 42 kJ/kg clinker and the calcination degree decreased by 5.6 %. The better top cyclone efficiency results in a preheater dust reduction of 42 g/Nm³. At the same time, the fuel substitution rate increased by 6.4 %, even though the calorific value of the SSW that was used during the audit in 2012 was higher than the typical values for this fuel.

Table 4.VI: Audit results for the clinker cooler

Main parameter	Unit	2017	2012
Secondary air volume	[Nm³/kg clinker]	0.43	0.33
Secondary air temperature	[°C]	1,068	1,099
Tertiary air volume	[Nm³/kg clinker]	0.47	0.58
Tertiary air temperature	[°C]	650	694
Cooling air	[Nm³/kg clinker]	1.81	2.13
Clinker exit temperature	[°C]	170	201
Recovery efficiency	[%]	66.78	60.93
K factor	[-]	1.22	1.04
Cooler load	[t/d/m²]	48.30	44.74

While the specific cooling air was reduced, the secondary air volume has increased. The tertiary air volume as well as its temperature have decreased since 2012. Due to better heat recovery, the cooler efficiency has increased resulting in a lower clinker temperature.

Summarizing, it should be stated that the modifications that were made since 2012 have a positive effect on specific heat consumption, alternative fuel rate and production volume but there is still room for improvement regarding energy efficiency and process optimization.

4.5 Alternative Fuel Ash as Alternative Raw Material

One aspect of alternative fuels (AF) is the heat input that comes from their combustion. From another point of view, their ash can be seen as alternative raw material (ARM), because it contains elements that are vital for the formation of clinker. As described in chapter 1.2.1, the compounds that are bound in the clinker phases are calcium oxide (CaO), aluminate (Al_2O_3), ferrite (Fe_2O_3) and silicate (SiO_2), as shown in Figure 4.18. Petroleum coke is not considered in this chapter. On the one hand it is not an alternative fuel and on the other its ash content is distorted because of preheater dust in the coal mill.

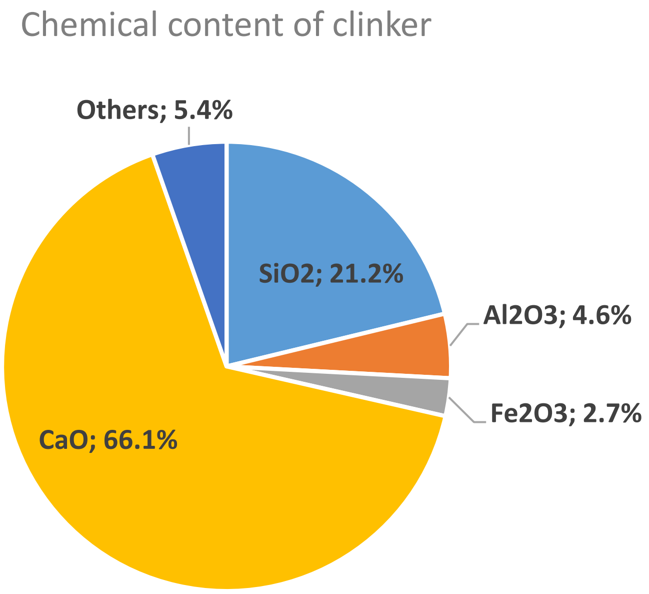

Figure 4.18: Chemical content of clinker

Table 4.VII shows that these compounds are present to a great extent in the ashes of several fuels.

Table 4.VII: Chemical content of ashes, %

	Main burner ash			Precalciner ash		
	Pipe 2	**HCF**	**Fall Through**	**SSW**	**Line 3**	**ISF**
SiO_2	26,2	29,7	26,6	26,6	26,6	25,2
Al_2O_3	28,9	21,1	14,4	14,4	14,4	23,9
Fe_2O_3	15,1	15,1	24,3	24,3	24,3	17,1
CaO	28,6	34,3	33,4	33,4	33,4	31,9
MgO	3,2	3,7	3,8	3,8	3,8	3,6
K_2O	0,2	0,4	0,7	0,7	0,7	0,3
Na_2O	1,3	2,0	2,4	2,4	2,4	2,2
TiO_2	3,1	2,8	2,3	2,3	2,3	6,2
P_2O_5	1,0	1,0	0,0	0,0	0,0	1,2

Table 4.VIII indicates the impact of the fuels on the Clinker composition. 105 t of clinker contain 2.74 t or 2.6 % of fuel ash. 2.2 t or 80 % of the ash is generated at the precalciner, 0.5 t or 20 % at the main burner. Assuming a production volume of 2520 t of clinker per day, 65.5 t of raw materials are saved due to the contribution of AF-ashes. As a consequence, alternative fuels should be considered not only as heat source but also as alternative raw materials. Their use reduces the demand for natural resources.

Table 4.VIII: Mass flow and ash content of fuels and clinker

	Main burner			**Precalciner**			
	Pipe 2	**HCF**	**Fall Through**	**SSW**	**Line3**	**ISF**	**Clinker**
Mass flow [t/h]	2,6	1,4	0,5	7,7	3,7	2,1	105,1
Sulphur [%]	0,2	0,2	0,8	0,8	0,8	0,3	-
Ash [%]	10,9	11,1	15,9	15,9	15,9	18,9	2,7
Ash [t]	0,3	0,2	0,1	1,2	0,6	0,4	2,8
Cl [%]	0,9	0,6	0,5	0,5	0,5	0,4	0,1

5 Optimization Strategies

Since the target of this Thesis is to not only quantify and analyse the weaknesses but also to unveil room for improvement, the last chapter deals with the formulation of optimization strategies.

5.1 Process Stability

The reason, why the stability related strategies were prioritized in this chapter compared with the energy efficiency measures is that efficiency can only be achieved with a stable process. Besides the creation of more room for efficiency measures, it should be a target for every kind of plant to have a stable process and clear operating parameters. Though the precalciner involves lots of benefits such as the higher production capacity, lower fuel quality requirements and reduction in heat consumption, it is still not operated at its optimum.

Firstly, the gas velocities at the tertiary air outlet and the orifice are not adequate, which has an impact on pressure disturbances in the best and blockages in the worst case. It has to be ensured that material can neither enter the tertiary air duct nor fall down into the orifice. Concerning the tertiary air duct there exists a serious flow problem due to the layout of the tertiary air ring duct around the precalciner. Furthermore, attention has to be paid to the prevention of refractory losses in the range of the orifice.

Secondly, the fuel feed, which is taking place in an uneven and discontinuous manner, entails CO-, pressure and temperature disturbances, which interfere with the process and inhibit a stable operation at specified parameters. To maintain the temperature level at fluctuating calorific values, impurities and varying fragmentation of the fuels is a difficulty that is associated with the use of alternative fuels, which are not as homogeneous as fossil fuels. However, the impact of the heterogeneity can be attenuated with a good automatic control. Optimization of the automatic control should be a target as well as ensuring the quality of the used material. The feeding system should be optimized to allow a stable and continuous fuel dosing.

Regarding the automatic control, namely the Kiln Master, the response is aggressive. Small temperature deviations or fuel failures are aggravated by very short response times as well as abrupt and severe intervention of the control system.

Finally, the malfunction of the coal feeding system at the precalciner, which is described in chapter 4.2.1, has to be clarified. The elimination of these periodically appearing CO-peaks would significantly contribute to the solution of the CO-related issues.

The strategies for process stability can be concluded as follows:

- Adaption of the gas velocities in the orifice to avoid material falling through and in the tertiary air outlets to avoid blockages
- Prevention of refractory losses in high gas speed zones
- Realisation of reasonably steady and uniform fuel feed with constant calorific value
- Adaption of the Kiln Master response time regarding fuel feed
- Inspection of the petroleum coke feeding system

5.2 Energy Efficiency

In the last few years, efforts were undertaken to reduce the specific heat consumption, cut down on fuel costs, increase the throughput and enhance the product quality. Regarding the energy efficiency, the kiln audit proved that there is still room for improvement. Energy efficiency implicates not only lower fuel consumption but also less CO_2 emissions and advanced processes, which, in the long term, help to save costs.

The clinker cooler produces exhaust gas, which accumulates at high temperatures and volumes. At the moment, it is used only partially in the cement mill. Further usage of this exhaust gas would significantly increase the energy efficiency. A feasible option would be to use it for the drying of alternative fuels. Drying of petroleum coke in the coal mill is not possible due to the high oxygen content of the cooler exit gas. Reduction of the moisture content of the alternative fuels reduces the energy demand in the kiln because the water vaporisation heat is omitted. A future installation of a dryer for alternative fuels is already planned.

Substantial volumes of false air that leak into the kiln system at various points deteriorate the specific heat consumption. On the one hand, the excessive air volumes that enter the system at ambient temperature absorb a lot of heat while diluting the hot process gas. This additional heat has to be supplied to the kiln in order to enable the desired reactions. On the other hand, the additional gas volumes have to be transported throughout the whole system until the top of the chimney. This implies a higher power consumption for the fans and a larger layout of plant units.

The high clinker temperature and the low tertiary and secondary air temperature indicate optimization potential at the clinker cooler. Another approach is to recover the heat after the cooler directly from the clinker, but due to the low temperature niveau, the application of the recovered heat is questionable.

Carbon monoxide in the exhaust gas involves not only incomplete combustion but also heat losses. Carbon monoxide still has a relatively high calorific value, which vanishes through the chimney. Therefore, the fuel feeding system and the automatic control have to be optimized to establish stable conditions for complete combustion.

When the CO concentration in the precalciner reaches constant values, the combustion air volumes can be adjusted to maintain slightly oxidizing conditions. The advantages are the same as for the reduction in false air. Furthermore, it has to be stated that air mainly consists of elements that are not even participating in the combustion reaction, but though, they have to be heated and thereby consume energy.

Stabilization of the temperature levels would allow an adjustment of their default values. Specifying the temperatures at the precalciner and rotary kiln at minimal values that still provide conditions for reasonable reaction rates represents a lever to reduce the fuel consumption.

Due to the fact that the wall losses represent a substantial proportion of the total heat losses, insulation is an opportunity to mitigate the effect of radiation and convection. However, the disturbance of the temperature regimes across the walls of preheater, precalciner and rotary kiln has to be avoided. A technically viable solution for heat recovery or insulation is not in sight from today’s point of view.

To improve the thermal energy efficiency, the following plan of action is recommended:

- Further usage of the cooler exhaust gas
- Reduction of false air volumes
- Improvement of cooler performance

- Reduction of the CO concentration in the flue gas
- Reduction of combustion air and therefore flue gas volumes
- Stabilisation of temperatures at reasonable levels

5.3 Conclusion and Outlook

Due to its high energy demand, the cement industry is and will remain a field of research for energy engineers. The most important targets are to reduce the fuel requirement and emission of climate-relevant gases and pollutants whilst maximising alternative fuel rates in order to conserve limited natural resources and cut down on costs. In this respect, good progress has already been made. Concerning the standard-technique pyroprocessing unit, the largest potential can be found in the use of the waste gases, reduction of false air and mitigation of wall losses. Insulation would be a reasonable first approach in order to avoid wall losses. A challenge thereby are the complex chemical reactions taking place during the clinker burning process and the limitations of deployed materials.

To improve the energy efficiency on a larger scale, new processes have to be investigated. Fluidized bed sintering technologies allow a reduction in specific heat consumption on a small scale but their process control seems to be more complex. Furthermore, the pilot plant is operated only with high-quality fuel, increasing operation costs compared with the existing processes.

Sewage sludge is an alternative fuel that is gaining in importance. A viable solution for the cement industry would be the mono incineration of the sludge followed by the recovery of phosphorous, a valuable resource for the fertiliser industry. Therefore, efforts have to be made to find economically and technically feasible solutions for the recovery process.

On the long term, further CO_2 abatement is only possible by applying carbon capture technologies. In opposition to the greenhouse gases resulting from the combustion of carbonaceous fuels, CO_2 emissions originating from the decarbonation of limestone and dolomite cannot be avoided. Thus, CCS might become an emerging technology in order to reduce the impact of the cement industry on the climate.

A substantial aspect of alternative fuels is their character as fuel on the one hand and as alternative raw material on the other. Due to the fact that the majority of the constituents of alternative fuel ashes are bound in the clinker, raw materials are conserved.

Finding a way to mitigate the wall losses of a rotary kiln or to use the waste heat without disturbing the process could be an interesting topic for further research. Investigations of the flow behaviour and combustion characteristics of the precalciner would allow a better understanding of the processes taking place in its inside. In order to qualify a statement, a series of measurements and subsequent analysis or simulation would be necessary.

Regarding the kiln audit, a clearer standard procedure and a less complex balancing tool should be implemented. Periodic and reliable energy audits are vital instruments to identify room for improvement and assist in finding the right process optimization or energy conservation strategies.

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