



**KTH Industrial Engineering  
and Management**

# Effective Use of Excess Heat in a Cement Plant

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## **Master of Science Thesis**

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## **Abstract**

The report investigates the feasibility of accessing waste heat at kiln 7 in the Cementa AB cement plant in Slite, Gotland. The background is provided, with a description of the cement manufacturing process. Most of the report concerns itself with the heat transfer capabilities of the plant, therefore a short description of the heat flow within the most essential equipment is provided.

The investigation follows a set of steps to derive the conclusion. The first step investigates previous studies to obtain the three most feasible heat sources. The second step investigates the available heat of the selected sources. In the third step, accessing the source is discussed and investigated for both convection and radiation heat transfer methods. It also includes the sizing of the required heat exchangers. Using the new sources, the connection possibilities to existing infrastructure and its benefits are investigated in step four. The connections were made to the existing infrastructure used at kiln 8 for electrical generation and district heating supply. The selections of the most feasible solutions are provided based on heat recovery, payback period and practicality. The final step in the study provides for the final design, which consists of three possible connections or all of them combined.

In the conclusion, the final design would provide for a reduction in oil burned, fuel consumption and CO<sub>2</sub> emissions and an increase in electricity generated by the existing system. It is recommended that only one of the three connections be installed.

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# **1 Introduction**

## **1.1 Motivation**

The cement industry is an energy intensive industry. The cement manufacturing process demands large amount of energy, with a large amount of this energy lost due to inefficiencies. Throughout history, various new design and equipment improvements have been made in order to increase efficiency, while maintaining good quality products. Most of the energy losses occur in the form of heat loss, with improvements relating to the combining and reusing of heat for drying and other production purposes within the plant.

Cementa AB recognized the potential for reusing lost heat outside the production process at their cement plant in Slite, Gotland, and together with Vattenfall AB and Gotlands Energi AB (GEAB), undertook projects in order to tap into the heat lost from certain parts of the heat intensive processes. The projects focused on the newest section of the plant, kiln number 8. Heat exchangers were connected to two of the hot gas outlets in order to use the heat for steam generation, which is used to generate electricity from a steam turbine. The other project also used one of the same gas outlets, and Cementa AB together with GEAB, installed a system that uses the heat from the gas for supplying heat to the district heating system in Slite. These projects managed to benefit the plant through reducing electrical costs by generating electricity from excess heat, as well as obtaining additional income and providing benefit to the community through the supply of heat to the district heating system.

Although the planning pointed to good returns, the desired outcomes were never achieved, with average electrical production in 2011 only reaching about 55 % of the design values. Additionally, the combination of district heating and electrical generation on the same gas outlet line, has led to prioritization of heat. The consequence was that the prioritization of the district heating has led to lower electrical production, with the overall shortcomings of the equipment also leading to lower heat production. To make up for the lack of heat for district heating, oil burners are used as backup. Identifying the problem and improving the existing system became an important aspect of this study.

## **1.2 Aims**

At the same cement plant, they have an older and smaller cement manufacturing section, kiln number 7. In an effort to replicate and improve on the system at kiln number 8, Cementa AB intended to investigate the feasibility of installing a similar heat recovery system in kiln number 7. This task was handed down to a student completing a master's degree at the Royal Institute of Technology (KTH), as part of the students master's thesis.

The nature of the study and the field required the student to conduct the study in different parts, each with different objectives and outcomes. Firstly, the student had to familiarize with the processes involved

and the heat flow within the cement manufacturing plant. Secondly, the student had to evaluate the specific conditions and available potential for accessing the heat at kiln number 7. Thirdly, the student had to investigate the possible improvements that could be made with the new system and uses for the heat, allowing for the identification of the most suitable connection and ending with a detail discussion of the final solution and savings it can contribute.

The first part of the study required the student to develop an understanding of the cement manufacturing process. This understanding extends to the equipment used and the purpose thereof. The reader is made aware of the basic concept and steps behind the manufacturing process, which would lead to a better understanding of the proposed solutions. The flow of heat could then be evaluated in detail through using the available sources.

The next step was to use the available information in order to determine the system boundary for the study. Using previously conducted studies of the system, accurate assumptions could be made for the available heat sources. The feasible heat sources were identified and compared to newly calculated values.

Accessing the heat is the priority for the analyses. The student had to investigate possible ways for collecting the heat and the size of the heat exchangers required, which would allow for more realistic generating estimates. As part of the investigation, initial estimations had to be made on the required equipment and connections that would be required.

Ultimately, the aim was to determine a cost effective solution, with a good payback period and a reduced environmental impact. Investigation of the current uses by the other installed system had to be made to evaluate the possible saving contributions that could be made by the new system. Each of the equipment and connection possibilities had to be investigated, followed by all the possible connections that could be made to the existing systems. The various connection possibilities had to include an accurate financial gains and capital cost analysis and an improved heat recovery analysis in order to identify the most suitable setup. The final setup could then be discussed in more detail, providing for the conclusion and best solution for the company.

The financial gain or savings for the plant had to be calculated for its future implementation, allowing the student to identify the highest return on investment. The investigation therefore had to include a detailed investment analysis, which could be used by Cementa AB to request funding for conducting the project from its parent company, Heidelberg Cement Group, together with a recommendation on the options available.

### **1.3 Exclusions and limitations**

Cementa AB intended to obtain maximum benefit, while minimizing the cost as well as the impact on the existing processes. In complying to these requirements, the design had to exclude any modification to existing process equipment, other than simple tie ins for diverting non-process related flows, such as

heated gas being vented. It also excluded the acquisition of any high cost equipment, such as a new steam turbine, and limited the sources to heat not used by any existing processes, hence previously lost heat. It did allow for the acquisition of new heat exchangers.

The sources of heat losses were limited to kiln 7 and the highest level losses from that kiln. The study allowed for connecting to the existing systems, but excludes the studying and modifications of any of the kiln 8 systems or processes.

## **2 Cement Plant Overview**

The plant has a long history which is discussed briefly in this chapter. The company profile provides for the background to how the plant came to be and the current setup came to exist.

Various equipment and methods exist for manufacturing cement, of which many different volumes of books and papers have been written. In order to avoid excessive discussion into the processes involved and equipment that could be used, this section will only focus on the most relevant equipment and processes used by the current setup found at kiln number 7, located at the Cementa AB plant in Slite, Gotland.

### **2.1 Company profile**

Cementa AB is part of the global Heidelberg Cement Group (Heidelberg). Heidelberg has about 75 000 employees globally. Cementa AB has 3 cement production plants and 15 distribution centers in Sweden. The production plants are located in Slite, Degerhamn and Skövde, with Slite being the largest. The Slite plant has about 400 permanent and subcontracted personnel and produces about 2 million tons of cement a year, of which 50 % are exported. The plant also incorporates an electrical generator and is also the supplier of heat to the Slite district heating system (Ahlberg & Udd, 2009).

Throughout the years, Cementa AB's environmental improvement program has resulted in a 90 % reduction in emissions of nitrogen-oxides and sulphur. Further improvements include the reduction of fossil fuels by replacing it with alternative fuels. The Slite cement plan is one of the most modern and energy efficient cement plants. (Grönwall, 2010)

#### **2.1.1 History of the Slite plant**

In 1916 a company previously manufacturing lime, Slite Cement och Kalk AB, started the construction of its first cement plant in Slite. The plant started producing cement in 1919, with its design allowing for multiple extensions. The first of such extensions were completed in 1929, through installing an additional kiln, adding a 200 ton per day production capacity. (Ahlberg & Udd, 2009)

In 1931, another company, Skånska Cement AB, acquired majority shares in the Slite company and started adopting a new marketing strategy. Under the new ownership, kiln number 1 was modernized in 1935, together with a storage capacity increase through the construction of additional cement silos. (Ahlberg & Udd, 2009)

The company realized that having two kilns at the plant opened up the possibility of manufacturing two different types of cement at the same time. In order to achieve this, in 1936, the company installed an additional cement mill and two more sludge silos. During this time, bulk cement shipping started to become popular, adding to the demand for large storage facilities. (Ahlberg & Udd, 2009)

An increase in capacity was required, which was added in 1939, through the construction of the third kiln. The new kiln increased the production capability of the plant by 400 ton per day. The upgrade occurred at a bad time, with the onset of World War 2 a few years later. (Ahlberg & Udd, 2009)

The onset of World War 2 forced the cement industry into low production and restrictions, with some years only producing for 7 months in a year. Only after the war could the production return to its normal values. (Ahlberg & Udd, 2009)

Further capacity increase of 600 tons per year came about in 1950, with the construction of the fourth kiln. During the mid-1950's the company adopted a long term strategy, which would see to drastic changes within Sweden's cement industry. (Ahlberg & Udd, 2009)

The company decided that all increases in demand will be met by a few large plants, which would be gradually expanded. One of these plants being the Slite plant, which started undergoing major expansions. The aging kiln number 2 was replaced with a new kiln number 5 in 1961. Shortly after, in 1963, kiln number 1 was taken out of service. In 1964, a new dry mill process was introduced and new equipment installed to support the process. This happened together with the installation of the sixth kiln, which added a capacity of 1 000 ton per day, making the Slite plant the largest cement manufacturing plant in the company. This capacity was increased even further with the installation of kiln number 7 in 1970. (Ahlberg & Udd, 2009)

Cementa used to be the marketing branch of Skånska Cement AB. In 1969, it was decided to rename the company Cementa AB. The ownership changed soon afterwards, in 1973, when Eurec Industri AB acquired the majority shares in Cementa AB. (Ahlberg & Udd, 2009)

During the 1970s, the cement industry in Sweden underwent a period of difficulties, due to lack of demand and rising fuel costs. As a consequence, the plant had to become more efficient and competitive. Kiln number 5, still using the old wet method, was decommissioned in 1973. The energy intensive wet kiln technology was completely replaced across the rest of Sweden in 1979 by the dry kiln technology. Shortly afterward kiln 5, in 1977, both kiln 3 and kiln 4 were also decommissioned. Keeping with the original strategy of fewer larger plants, the company started closing down all the smaller cement plants in the country. The only remaining plants were the three large upgraded plants in Slite, Degerhamn and Skövde. (Ahlberg & Udd, 2009)

The production capacity of the Slite plant was increased significantly with the addition of kiln number 8 in 1979. The project was undertaken following the required approval of mining near the plant, as well as the connection to the electricity grid and the availability of a bulk carrier vessel. Kiln number 8 had a capacity of 4 700 tons per day, which was increased to 5 700 tons per day after the installation of a calcining system in 1991. Kiln 6 stopped operation in 1991, but is still located in its original position, northwest of kiln 7. (Ahlberg & Udd, 2009)

The new owners managed to acquire the Swedish government's shares of Cementa AB in 1992. Following the acquisition, the company was renamed Eurec AB. In 1996, the company was acquired by Skanska AB, which incorporated the company with Scancern AB. This new management lasted until 1999, when Heidelberg Cement AG took over Scancern AB and Cementa AB. (Ahlberg & Udd, 2009)

## 2.2 Production process

Various production methods and equipment exist, all of which achieves the same chemical processes. The focus of this discussion will be on the specific process and methods used at kiln number 7.

Mineral compounds containing the main components of cement are mined on site. These components are lime, silica, alumina and iron oxide, which when combined with specific auxiliary materials are used in manufacturing the most common type of manufactured cement, Portland cement (Duda, 1985). The next process involves reducing the raw material through crushers. The Slite plant uses a large hammer crusher, reducing the size to maximum of 80 mm. The crushed raw material is transported to storage piles, where mixing of the raw material takes place in order to achieve an optimal quality mixture. The storage piles also acts as a buffer supply for the raw mill (Grönwall, 2010).

Simultaneous grinding and drying of the crushed material occurs in the combined dryer-roller mill. The crushed material is fed from the top into the roller mill, which lands on the grinding table. Centrifugal forces throw the material in the path of the grinding rollers which crush it. Hot air, sourced from the kiln, is used to push the fine particles (referred to as raw meal) up through a classifier, separating and returning the large particles to the grinding table. The hot air simultaneously also dries the incoming raw material, which increases the efficiency of the grinding process. (Duda, 1985)

The dust (raw meal) filled gas is sent to an electrostatic precipitator filter, which separates the dust particles from the gas. The gas also carries with it some unwanted acidic particles, which are washed away in a wet scrubber and later neutralized using ground limestone in the scrubber slurry. Following the filtration, the raw meal is then transported and stored within raw meal silos. (Grönwall, 2010)

The raw meal is then ready for undergoing the various processes necessary to form clinker. The first part of this process involves pre-heating and drying of the raw meal, which is conducted using a suspension preheater at temperatures below 700 °C (Kiln Performance Tests Task Force, 1992). This is a tall structure containing a vertical arrangement of five cyclones in series. Heated gasses from the kiln is passed upwards through each cyclone, heating the raw meal which is fed from the top down, exposing it to hotter temperatures as it moves to lower cyclones (Ibrahim, 1986). The starting composition consists of calcite ( $\text{CaCO}_3$ ), quartz ( $\text{SiO}_2$ ), clay minerals ( $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-H}_2\text{O}$ ) and iron ore ( $\text{Fe}_2\text{O}_3$ ) (Kiln Performance Tests Task Force, 1992). The raw meal then enters the rotating kiln, where it slides and roles counter to the hot gasses at the other end (Taylor, 1997), exposing itself to three main phases within the process.

Kiln number 7 is a large steel cylinder fitted with refractory and tilted slightly towards the burner, with a 4,4 meter outer diameter and spanning a length of 60 meters. The dried raw meal undergoes calcination of  $\text{CaCO}_3$  and concurrent binding of  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ , activated  $\text{SiO}_2$  and  $\text{CaO}$ , in the range of temperature between 700 °C and 900 °C (Kiln Performance Tests Task Force, 1992). Transition to Belite ( $\text{C}_3\text{S}$ ) occurs between 900 °C and 1 300 °C and as soon as the new compounds reach the burner, they experience sintering above 1 300 °C (Boateng, 2008). These temperatures are achieved through a direct firing burner, using coal as primary fuel, situated at the end of the rotating kiln line. Newly formed clinker leaves the kiln at very high temperatures.

Rapid cooling down of the clinker is followed in the clinker cooler. During the cooling stage, the molten phase,  $3\text{CaO}\cdot\text{Al}_2\text{O}_3$ , forms, and if the cooling is too slow, alite may dissolve back into the liquid phase and appear as secondary belite (Tahsin & Vedat, 2005), reducing the quality of the final product. The cooling is needed in order to improve the quality, allow for transportation and to reuse the heat within the previous processes (Taylor, 1997). Within the clinker cooler, cold air is pumped from the atmosphere through the clinker. The convection heats up the air, which in turn is partially used to supply fresh air to the burner and partially vented through a filter, after which the heat is dissipated to the atmosphere via a chimney.

The newly formed clinker is stored within clinker silos, followed by the grinding process in the cement mills which, together with additives such as Gypsum, forms the final cement product. From here the cement is stored in silos until collected by trucks or ships for further distribution (Grönwall, 2010). The plant has its own truck loading facilities and harbour on location.

## **2.3 Heat flow Source to outlets**

Studying the heat source and the flow from it, are the focus of this section. The report is concerned with the heat flow in kiln 7 only, therefore only kiln 7 will be discussed. It describes the flow of heat up to major outlets or processes requirements. The description of heat flow through the system should be read together with Figure 2 for improved understanding.

### **2.3.1 Burner**

Energy is added to the system, through the direct firing burner (A) situated at the lower part of the rotary kiln. The burner in kiln number 7 is currently being fuelled by coal, although future developments will add a mixture of alternative fuels (Stover, 2011).

### **2.3.2 Rotary kiln**

The rotary kiln is made out of a layer of refractory bricks surrounded by a steel shell. The high temperature used inside of the kiln is transferred through conduction to the outer shell, which is exposed to the surroundings. The wheels on which the rotary kiln rotates are called “tyres”. They are constructed

from steel and are loosely connected to the kiln shell, while supported by the rollers, which rotates the kiln and carries the weight of the kiln, as can be seen in Figure 1.

Fuel from the burner ignites and burns the oxygen in the supply air, which is a combination of secondary air and dust from the clinker cooler (B) and air and dust from the atmosphere (C). Air is also known to infiltrate through openings between the equipment and is referred to as false air (D) (Stover, 2011). Large openings at the hot end of the rotary kiln cause air to displace the hot secondary air from the clinker cooler. The false air increases the energy requirements in the system, by increasing the energy required to heat up the false air to the gas temperature (Duda, 1985).

The heat allows for the necessary chemical reactions (E) to occur within the rotary kiln. A large amount of heat is absorbed by the material entering the kiln (T) which undergoes the various chemical reactions. These reactions include endothermic reactions, such as evaporation, decomposition of clay and dissociation of  $MgCO_3$  and  $CaCO_3$ . It also includes exothermic reactions, such as the formation of organic clay components, dissociation of  $FeS_2$  and formation of clinker. (Stover, 2011)

The shell loses large amounts of heat through radiation and convection (F). Additionally, air is pumped over the shell surface using nozzles (see Figure 1), on the burner side. This is done in order to cool the outer shell to create material build-up, which in turn protects the refractory used inside the kiln. The build-up is a consequence of the material melting at the high temperatures and cooling down against the surface. It is known that cooling of the kiln shell can increase the refractory's lifetime by up to two times that of refractory without cooling (Duda, 1985). Air forced over the kiln shell, together with wind, causes convection losses (Stover, 2011).

Heat also enters the system through the machinery used (G), such as the motors used for rotating the kiln. Heat finally leaves the kiln in the form of hot air (H) and dust being transferred to the pre-heating cyclones.

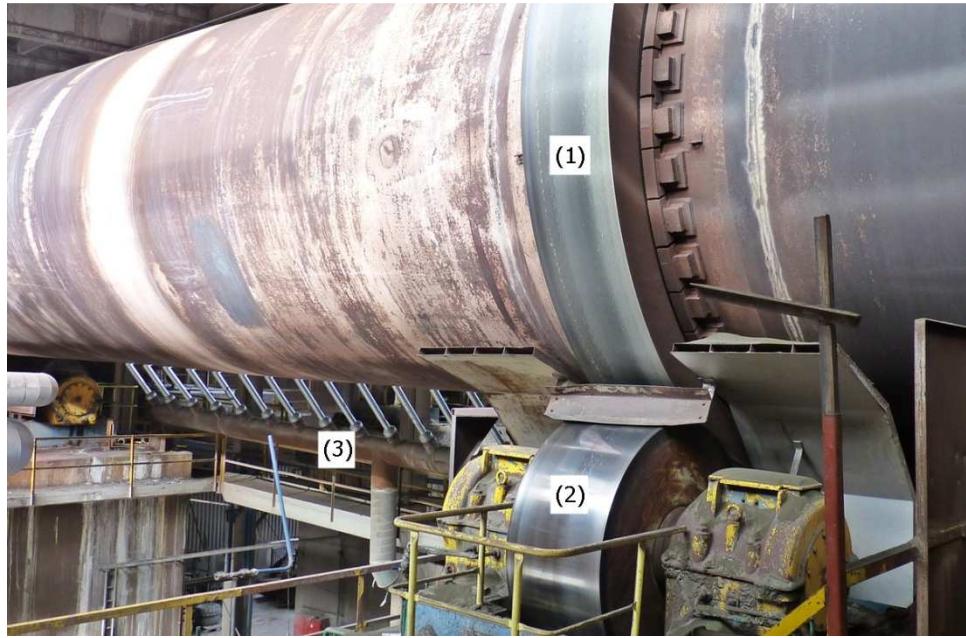


Figure 1: Rotary kiln number 7 with indicated tyre (1), roller (2) and air nozzles (3).

### 2.3.3 Bypass air

If excess volatile particles are present in the feed or fuel, such as sulphur or chloride, they will vaporize in the burner and condense in the preheater, causing build-up (Alsop et al., 2007). In order to avoid the plugging of the cyclones from this build-up, a bypass system is installed which removes a portion of the kiln exhaust gasses, thereby reducing the amount of harmful materials from the process (Duda, 1985). The system experiences heat loss caused by the bypass air and dust (I) escaping via the bypass system.

### 2.3.4 Preheating cyclones

Colder air and raw meal (J) is conveyed to the cyclones, which absorbs much of the heat coming from the rotary kiln, which then exits the system at a much higher temperature into the rotary kiln. Additionally, air infiltrates (K) through gaps in the equipment.

The heated cyclones lose heat to the surroundings through radiation and convection (L). The heat in the air and dust (M) which exits the system at the top of the cyclone tower is pumped through the cooling tower. More heat is also lost through movement of raw meal (T) from the preheater to the kiln.

### 2.3.5 Cooling tower

Hot gas and dust enters the cooling tower from the preheater cyclone. Cold water (U) is pumped directly into the gas, in order to cool it to the desired temperature, as per the raw mill requirements. The cooling tower also experiences some convection and radiation losses (V), due to its exposure to the environment. The cooled gas (W) is then pumped via a fan directly into the raw mill, where it is used for drying and transportation of small particles.

### 2.3.6 Clinker cooler

Cooling of the clinker is required in order to influence the structure, composition and grindability, which would improve the quality of the resulting cement. Cooling is also necessary to allow for easier conveying and reclamation of the clinker heat. (Duda, 1985)

The hot clinker (N) enters the clinker cooler from the rotating kiln. Cold air form the atmosphere (O) is then pumped over the clinker to cool it down. The clinker is cooled down through convection, with a large portion of the heated air leaving the cooler into the rotating kiln. A portion of the air is diverted to a filter (P), after which it is exhausted to the atmosphere. (Stover, 2011)

The clinker is conveyed out of the clinker cooler in a cooled down state, causing some heat within the clinker (Q) to be lost to the next system. The elevated temperature of the clinker cooler shell allows for heat losses, through convection and radiation (R), to the environment. The mechanical equipment used, contribute to adding heat to the system through its electrical motors (S). (Stover, 2011)

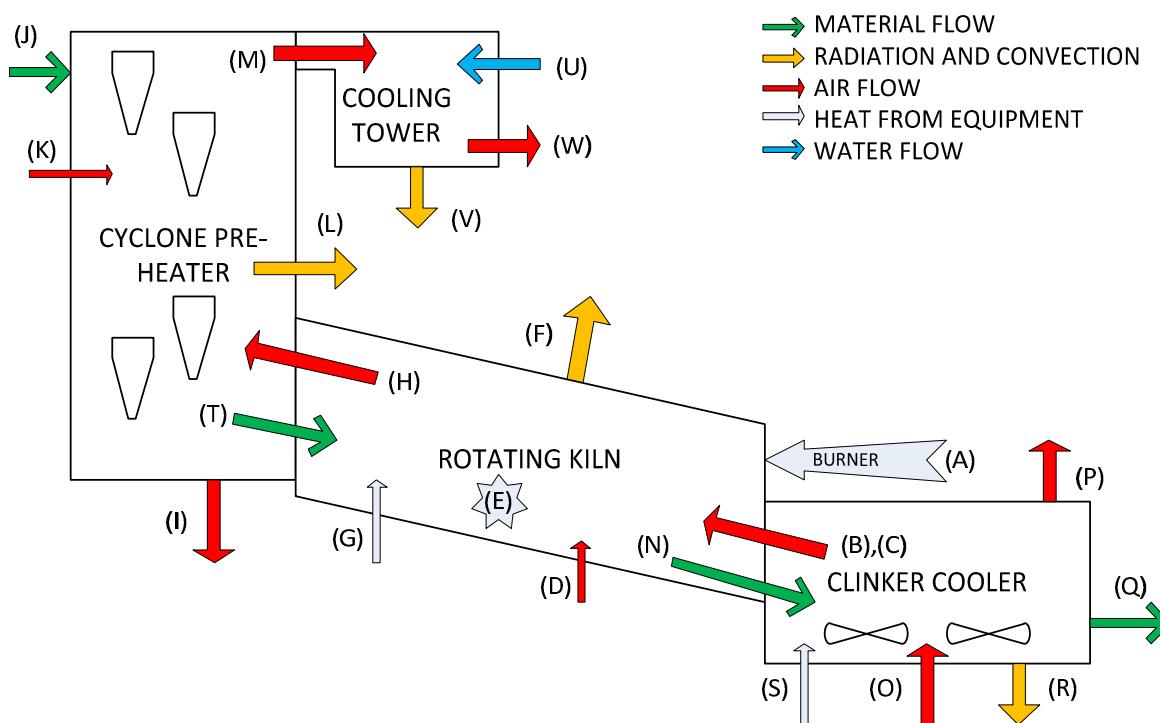


Figure 2: Diagram indicating the heat flow, including the losses and gains in the system.

## **3 Heat Recovery**

This chapter describes the system boundaries in which the study will be conducted and explores the possible sources of accessible heat through investigating previously conducted studies. By using the studies and analysing the results, it is possible to establish which of the heat sources can be considered “lost heat”, and also determine whether the accessing of this heat could influence the process, rendering it as an unacceptable source. The possible uses were explored followed by a connection with each source. Studying the costs, energy recovery and returns, a final setup was achieved. This section ends with the detailed discussion of the final setup and the conclusion.

### **3.1 Establishing the system boundaries**

The first part of analysing a system is to determine which parts constitute the system in question. Identifying the limits of the system allowed for a clearly defined boundary for which the energy and heat flows passing through this boundary can be analysed, providing results which can be used within the rest of the study. It is important to take into account that heat is added to the system by the coal fired burner, with much of the heat used within the processes and a large amount of heat is also recycled through to other processes, such as for preheating and drying.

#### **3.1.1 Method for determining the system boundaries**

The system boundary used in heat flow studies within the cement plant will be adopted, with the addition of the cooling tower, as can be seen in Figure 2 and Figure 3. The cooling tower is added due to its importance in analyses conducted further in the study.

The source of the heat, will have the boundary cut off at the inlet of the fuel, thereby the study excludes the flow of fuel to the burner and only include the heat caused by the burning of the fuel. The boundary will be located at the outer shells of the equipment and machinery involved. Any non-mechanical flows, such as electrical wiring and sensors, are excluded from the system. Equipment contained within machinery will have the boundary on the outer surface of the machinery, i.e. on surfaces exposed to atmosphere. The boundary will exclude any unnecessary equipment from the study by closing off the boundary at any exit of heated gasses or material which leads to direct venting or cooling into the atmosphere or surroundings, also excluding any equipment used for the purpose of venting. In the case of air being pumped into the system, the cut off boundary will be located at the outlet of the equipment.

Any heat absorbed and used within this system will be considered necessary for the process and operation of the plant and excluded as a possible source. The sources that will be considered will therefore only be heat that is lost, through whichever means, out of the boundary of the system.

### **3.1.2 System description**

With the previously mentioned boundary description, it is possible to establish the equipment involved at kiln number 7. The primary system will therefore consist of the kiln, burner inlet, clinker cooler, suspended preheater, cooling tower and bypass line.

For the system, the boundary will form around the equipment, with cut off at the top of the cooling tower where the gas exits to the rawmill. It also cuts off at the raw meal inlets into the cyclones. The bypass line will be cut off before entering the bypass filter. The kiln will be fully included, with exception of the motors used on the outside for rotation. The clinker cooler will be cut off at the venting exit, which leads to a filter and consequently the venting tower. The outlet points at the bottom of the clinker will be the boundary limit for the system.

The boundary established allowed for an accurate assessment of the heat which flows from the source and the losses occurring across the defined boundary. The boundary described applies to the study of establishing and quantifying the available sources of heat lost to the atmosphere, with the special case related to the cooling tower situated at the preheater cyclone gas exit. The inclusion of the cooling tower allowed for more accurate results related to the preheater cyclone gasses and the requirements of the raw mill.

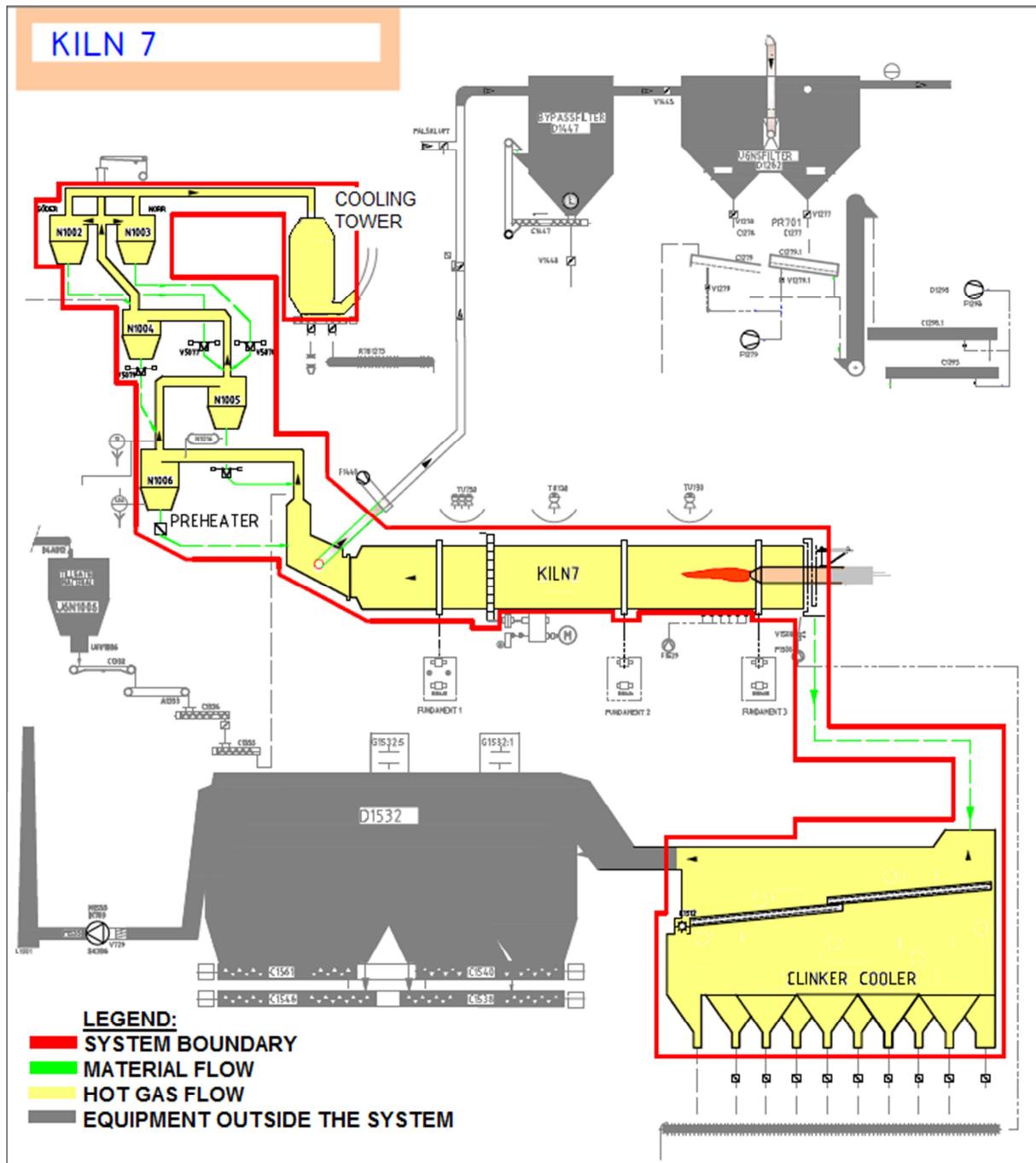


Figure 3: Diagram indicating the system boundaries and the nearby connections.

## **3.2 Data and measurements**

In order to establish an accurate evaluation of the heat losses and their magnitude, it is important to access historical data. Such data is available from various sources, including previous studies, measurement equipment and records from other companies.

Exploring similar studies provides a good starting point for further evaluation. First the studies need to be investigated for relevancy. After found relevant, they could be used to identify the location and type of heat losses. Measurement instruments found on site, could be used to obtain more accurate and relevant quantities, which were used to improve on the values of the studies, based on the new requirements and restrictions. These measurement instruments therefore needs to be identified and their locations established.

To obtain quantifiable values for the final analyses, calculations based on the available measurements were required. The sources vary, depending on the type of variable investigated and the availability of the measurement instruments.

### **3.2.1 System Audits**

Data on previous energy studies (system audits) conducted on kiln 7 has been made available by Cementa AB. Three system audits on the heat balance of kiln number 7 have been identified as applicable, which will be discussed in more detail.

The first audit was conducted in June 2006 in order to highlight areas of improvements and to create a reference of the state of the kiln. The second and more recent audit was conducted in April 2011, in order to record the performance of the kiln before replacing the burner. The third and latest audit was conducted in September 2011, in order to compare the performance before and after the replacement of the burner.

The latest two studies are considered more accurate, due to modifications and adjustments made to the plant and to the cement being manufacture from 2006. The studies were conducted in a period lasting two days each, using the measurements of that period. Both these studies can be considered accurate, with only 15,5 % and 6,6 % (respectively) of the heat calculated to be unaccounted for . (Stover, 2011). The outcome of the studies provides for a good and reliable guideline for reducing the heat source selection.

The results from the system audit for September 2011 indicate a significant amount of energy (64,4 %) that was not used by the processes (within the period of data collection), part of which has the potential to be used for other purposes.

It would be more productive to only investigate the largest sources of heat lost. The largest sources will provide the best location for capturing heat and if the heat source is found unfeasible, all smaller sources will immediately be eliminated. The calculated values provided by these reports, narrows down the possible selection of heat sources to heat from radiation and convection of the rotary kiln, cooler vent air

and raw waste gas and dust from cyclone towers with some additional operational restrictions (discussed later). The breakdown of the heat added to the system can be seen in Table 1, and the heat lost from the system in Table 2.

**Table 1: Inputs - Heat added to the system, from previous studies.**

Study Designation	2011-04-14		2011-10-19	
	Total Heat	Quantity (kW)	Total Heat	Quantity (kW)
Fuel from main burner	84,4%	48 178	92,3%	54 115
Sensible enthalpy	0	6	0	10
Kiln feed	1,4%	788	1,9%	1 100
Air	-1,8%	-1 044	-1,5%	-853
Mechanical equipment	0,7%	422	0,7%	422
Balance remainder (Error)	15,3%	8 728	6,6%	3 855
Total	100%	57 079	100%	58 649

**Table 2: Outputs - Heat lost from the system, from previous studies.**

Study Designation	2011-04-14		2011-10-19	
	Total Heat	Quantity (kW)	Total Heat	Quantity (kW)
Reaction enthalpy	37,8%	21 576	35,5%	20 812
Raw waste gas and dust losses	23,8%	13 557	23,7%	13 867
Bypass gas and dust losses	6,3%	3 609	4,8%	2 797
Cooler vent air	10,1%	5 771	13,1%	7 707
Incomplete combustion	0,1%	62	0,1%	64
Hot clinker	2,3%	1 319	2,5%	1 471
Radiation & convection losses from preheater	4,3%	2 448	4,0%	2 338
Radiation & convection losses from rotary kiln	14,7%	8 375	15,3%	8 986
Radiation & convection losses from clinker cooler	0,6%	362	1,0%	606
Total	100%	57 079	100%	58 649

### 3.2.2 Measurements

Historical and real time data has been made available through software, “Process Explorer”, which measures and records the input of all the installed sensors belonging to Cementa AB. Only a limited amount of these sensors are of concern to this study.

The company adopted a numbering system used across the plant, identifying its installation location and the sensor type. These numbers will be used throughout the calculations in order to simplify the referencing and usability of the report by Cementa AB. The sensors measuring the properties for more accurate calculations are therefore identified and discussed further.

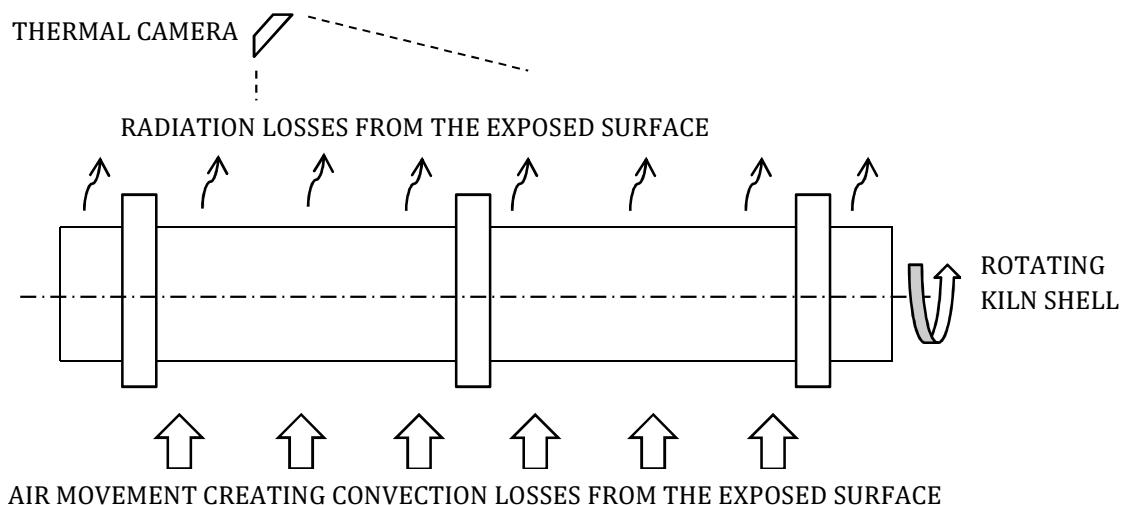
### **3.2.2.1 Atmospheric conditions**

The wind speed and air temperatures are mostly used for calculating the relative heat and convection losses of the sources. The air temperatures were obtained from Swedish Meteorological and Hydrological Institute (SMHI), and were taken from the Fårö weather tower near Slite. It provides the temperature in degree Celsius for each hour, from 9 March 2011 until 9 March 2012.

### **3.2.2.2 Kiln 7 measurements**

The studies conducted in 2011 were used to identify the largest sources of heat loss. These sources were identified as the cooler vent air, radiation of the kiln and the preheater gas. The measurements used to calculate the heat losses (calculation found in Section 3.3.2) is described in more detail in this section, with copies of the piping and instrumentation diagrams found in the Appendix.

The combined radiation and convection losses from the rotating kiln surface are the largest amount of heat loss. These losses were estimated using temperatures measured with the help of a thermal camera, the details of the estimations can be found in Section 3.3.2.2. The steel outer surface of the kiln reaches high temperatures, due to heat transfer from the burner, causing it to dissipate heat through convection, caused by wind and other forms of air movement, and radiation to the surrounding structures and environment. Figure 4, illustrates the heat loss mechanism in a basic manor.



**Figure 4 : Heat losses from the kiln surface.**

The preheater gas refers to the heated gas exiting the cyclone tower. The 2011 studies show that the gasses leaving the cyclone tower is the second highest source of heat loss. The process and equipment related to this section are described in Chapter 2.3.4. After the heat is absorbed from the gas into the raw meal, the gas is drawn out through the ducting into the cooling tower, after which it is transported to the rawmill.

The heat loss is estimated using temperature sensors inside the ducting. The gas flow and locations of the measurement instruments are illustrated in Figure 5.

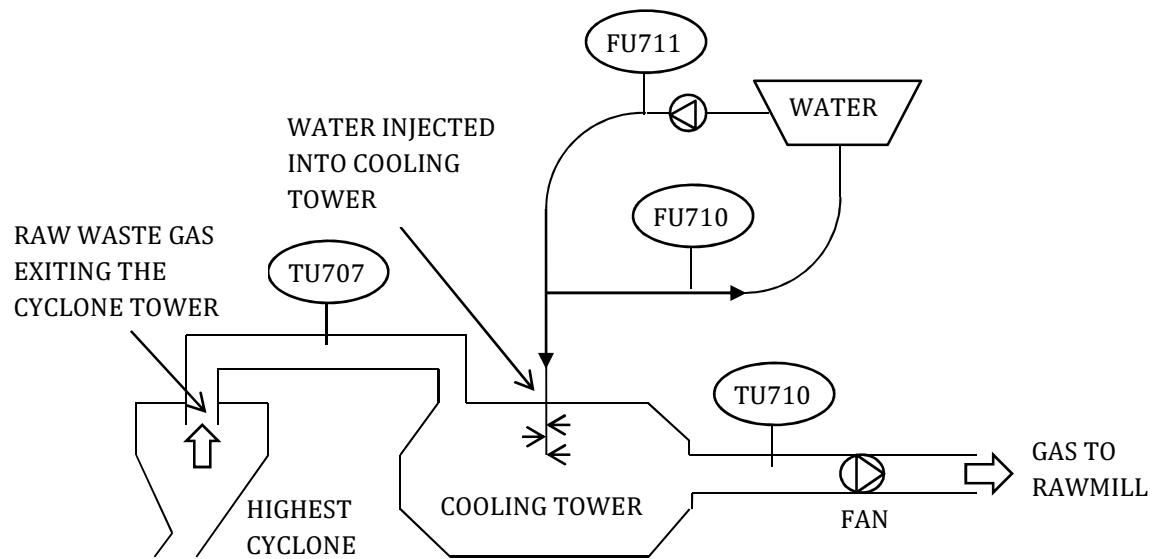


Figure 5 : Preheater gas flow and sensor locations.

The heated air, vented from the clinker cooler to the filter (cooler vent air), has been identified as the third largest heat loss. The heated air is currently not used in any process and is pumped into the atmosphere. Two measurement possibilities exist, before and after the filter as can be seen in Figure 6. The measurements from the sensor located before the filter were used by the 2011 studies and also in Section 3.3.2.1, for calculating the available heat. The measurements from the sensor located after the filter were used for the final calculations in Section 3.4.5.

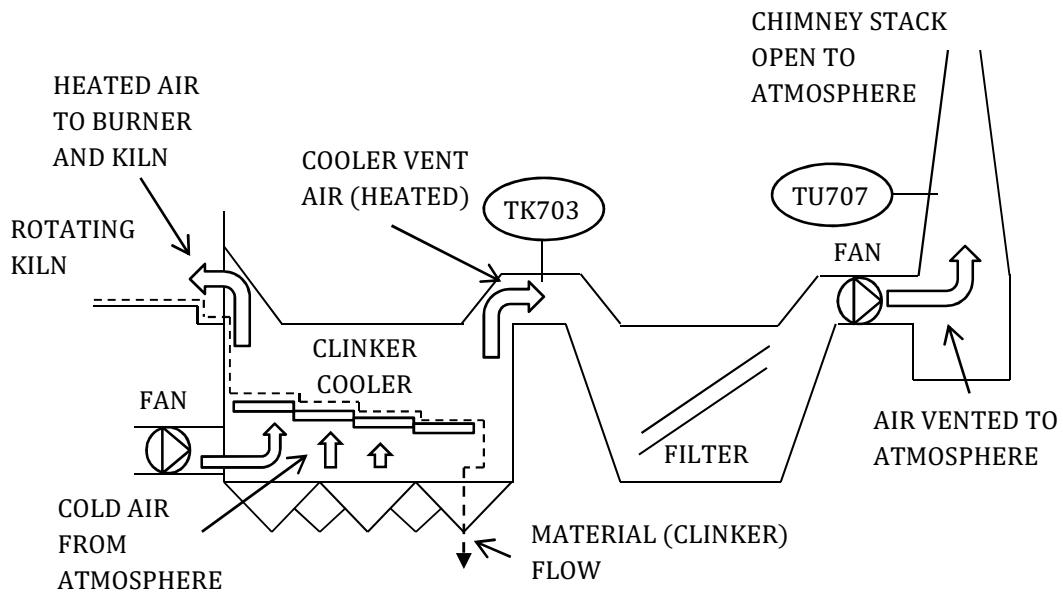


Figure 6 : Heat loss through air movement and sensor locations for the clinker cooler gas.

The temperatures of the vented gasses are measured using Pt100 sensors installed on site. The following temperature sensors have been identified as important for calculating the heat in the clinker cooler and preheater gas:

- TK702, located in the ducting of the clinker cooler exit gasses, after the filter and fan and used for calculating the heat in the gas which can be accessed using a heat exchanger;
- TK703, located in the ducting of the clinker cooler exit gasses, before reaching the filter and used for calculating the heat in the gas in order to compare with the 2011 studies;
- TU707, located between the cyclone tower's gas exit ducting and the water cooling tower and used for calculating the heat contained in the gas before cooling occurs;
- TU710, located on the exit ducting of the water cooling tower and used for calculating the heat in the gas after water injected cooling has occurred.

The kiln surface temperatures are not measured in the same way. Real time data can be viewed from the control room, but no spread sheet containing all the data was available. The data for a specific point in time were requested and received in the form of a graph as seen in Figure 8.

The cooling tower at kiln number 7 preheater cyclone gas outlet forms an intricate part of the heat calculation for the cyclone tower gasses. Water is pumped directly into the gas by the tower which would affect the output values. The volume flow added by the water is obtainable through the flow measurements conducted at the tower. The flow of cooling water occurs through a pump which is constantly operational and circulates the water in a loop. Water is extracted from this loop and is

calculated based on the difference in the volume flow before and after the water nozzles. The water flow measurement devices used can be seen in Figure 5 and numbered as:

- FU711, located before the cooling tower nozzles;
- FU710, located after the cooling tower nozzles.

These measurements are combined with both the system audit results and the kiln 8 measurements, depending on the variables being calculated.

### **3.2.2.3 Kiln 8 measurements**

The sensors at kiln 8 are used mostly during the study of the possible connections to kiln 7. They provide for more insight into possible operating times and calculating the possible contributions from kiln 7 tie-ins. Most of the variables used were obtained from “Process Explorer”.

The temperature sensors were mostly used to establish the operating times, such as for determining the hours in a year for which the gas temperature is too low. The sensors that were used were:

- TK813, located at the ducting running parallel to the district heating bypass, before the chimney;
- TK814, located directly after the clinker cooler, inside the heated gas ducting.

The flow of gas to the various heat exchangers at kiln 8's clinker cooler outlet was also an important variable for estimating operation times and possible contributions from kiln 7. The gas flows are regulated using dampers, for which each has a motor and a sensor indicating the level of openness. The damper sensors used in the calculations were:

- GK808, located on the main gas duct, running parallel to heat exchanger 2;
- GK809, located directly after heat exchanger 2, regulating the flow to the main duct.

The contributions of these measurements were essential for determining accurate operation times. More data was however required for the calculations, which were obtained from sensors not belonging to Cementa AB, although they are located on the plant.

### **3.2.2.4 District heating and steam measurements**

Due to the ownership of the heat exchangers and the control of the hot gasses being the responsibility of other companies, Vattenfall and GEAB, the instruments located near them are not part of the same system used by Cementa AB. The measured data used for those calculations were obtained from a separate source.

The electrical generation system, together with heat exchangers 1 and 2, are monitored 24 hours per day. Unfortunately, the data has not been stored electronically. All data measured were recorded by the operator on duty on a daily report filled in every 6 hours. This is done at the operators own discretion, resulting in many unrecorded time periods. It was also found that data are not recorded during a standstill, reducing the accuracy of the results even more. None the less, the data was filled in a spreadsheet, ranging

from January 2011 until January 2012, and the averages were used for conducting calculations. The data used included the following:

- Steam pressures, used for both heat exchangers;
- Steam and water temperatures, used for both heat exchangers;
- Electrical power output, generated by the steam turbine;
- Steam and water flows, for the steam line after heat exchanger 1 and before heat exchanger 2.

The district heating calculations were mostly related to the quantity of oil burned and demand available. These values were obtained from GEAB in the form of yearly energy reports. The reports indicate the total amount of heat used by the Slite community for each month of the year, with an indication of how much of the heat is obtained from burning oil. The supplied data sheets only contained the values for 2006 up to 2010. The total yearly values for 2011 were made available by Cementa AB's records.

### **3.3 Available Heat Sources**

An important step in establishing the effective use of excess heat in the plant is to identify and investigate the largest heat losses within the defined system. The sources can then be refined and combined with possible uses within the next chapter.

The aim was to identify the sources with the largest heat losses with the aid of previously conducted energy balances. It was then possible to improve on the identified sources using new calculations, historical measurements and more accurate assumptions. The historical measurement data were selected within a specific time frame, allowing for comparative results over a period of one year, which provides a new heat value which can be compared to the previous energy audits.

The newly calculated values provide for a good reference for further calculations. It also confirms the heat potential in the sources, minimizing the possibilities.

#### **3.3.1 Assumptions**

The assumptions made and listed here are for the all three sources. The gas flow assumptions apply to all calculations for gas flows. The kiln shell assumptions apply to the rotating kiln shell only.

In order to calculate the energy lost through the gas flow of both the preheater gas and the clinker cooler gas, we had to assume:

- The air duct to be a steady flow system, with a constant mass flow rate;
- The pressures to be constant throughout the ducting;
- Air leaks and heat losses are considered to be negligible;
- The dust concentration in the gas is constant and equal to the latest (2011) study.

The kiln shell calculations are made simpler through excluding the effects from the air blasting nozzles from the calculations. It is assumed that the air nozzles are vital for the operation of the kiln, and that the removal of these air nozzles will only be considered if it was found that a significant temperature drop would occur from a proposed heat exchanger, discussed in the next chapter.

#### **3.3.2 Available Energy**

Energy can be transferred to or from a given mass by heat and work (Cengel, 2003). The energy transfer considered for the calculations were heat transfer, for which the driving force is temperature difference. In order to analyse the heat potential for each source, it was necessary to look at the most suitable form of heat transfer (convection or radiation) for each those sources. As per the 2011 study results, only the three largest sources of heat loss have been investigated.

The calculations used were similar to the previously conducted audits. The previous audits were based on a specific document, “Execution and evaluation of kiln performance test”, containing information for

carrying out performance tests on the production part of the cement manufacturing plant (Kiln Performance Tests Task Force, 1992). Many methods and estimations are adopted from this document, in order to ensure comparable values and due to the established nature and accuracy this document provides.

The losses are considered to be potentially useable sources, placing importance on the heat transfer rate of each source. The heat transfer should be reflected as obtainable energy relative to the environment, which would give more realistic values for calculation purposes. The availability is also an important factor, to which the yearly available energy has been analysed. The relative energy of the sources were used to establish the relevance for further investigations.

There is also the question of availability, with a multitude of shutdowns occurring in the year, this aspect was considered important and therefore had to be included. The lack of availability in many time periods (down times) could influence the feasibility of using the source. In order to obtain a realistic and comparable figure of lost energy, the energy availability was calculated for each hour and summed together in order to obtain the available heat in kWh per year. The one year period<sup>1</sup> stretches from 9 March 2011 to 9 March 2012, which was selected purely from the starting time of this section of the work. This allows for comparable and up to date figures for each of the sources and incorporates the down times experienced during the year.

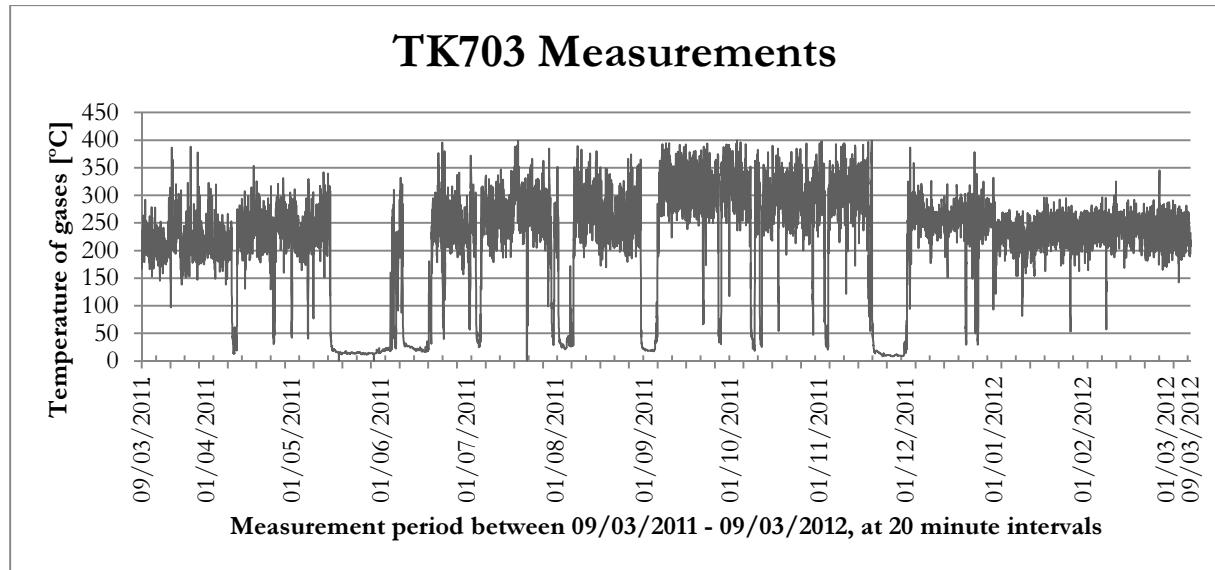
### **3.3.2.1    *Cooler vent air***

According to the 2011 studies (Table 2), heat lost due to venting of clinker cooler air to the atmosphere has an estimate heat loss of 5,7 MW (study 2011-04-14) or 7,7 MW (study 2011-10-19). These values will be compared to the newly calculated values (using Equation (1)) in this section, with comments on why the calculations deliver different results from the previously conducted studies.

The calculations in this section were made using the temperature measurements from the TK703 sensor, seen in Figure 7. The temperature changes a significant amount over time, with shutdown times amounting to weeks and the temperature measures around the range of 200 °C to 350 °C during normal operation.

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<sup>1</sup> The period used stretches over a leap year, therefore the amount of days is 366, as used in the calculations.



**Figure 7:** Temperature measurements for the clinker cooler gas (sensor TK703) over one year.

The clinker cooler air (gas) is vented to the atmosphere, the heat contained in the vented gas relative to the atmosphere is considered to be the heat loss from the system. The rate of heat lost relative to the atmosphere ( $\dot{Q}$ ) was calculated using the energy balance formula (Çengel & Boles, 2002). The temperature difference is taken as the difference between the measured gas temperature ( $T_{gas}$ ) and the measured atmospheric temperature ( $T_{atm}$ ).

$$\dot{Q} = \dot{m}C_p(T_{gas} - T_{atm}) \quad (1)$$

According to the standard industry guide for calculating heat losses, it can be assumed that the specific heat of the clinker cooler gas ( $C_p$ ) can be approximated as a function of the gas temperature in degree Celsius ( $\vartheta$ ), by using the specific thermal capacity of dry air ( $C_{p,dry}$ ) calculation (Kiln Performance Tests Task Force, 1992). This estimation was used in order to incorporate the equation with the measured values (over 26 000 measurements), as well as constraints on the availability of practically feasible software resources.

$$C_p \approx C_{p,dry} = 1,297 + 5,75 \cdot 10^{-5} \cdot \vartheta + 8,06 \cdot 10^{-8} \cdot \vartheta^2 - 2,86 \cdot 10^{-11} \cdot \vartheta^3 \quad (2)$$

The specific heat were calculated for each time step, of which the average value calculated is 1,3 kJ/m<sup>3</sup> K, which is similar to the results from the 2011 studies and the value obtained from using average values with related software (EES). Equation (2) provides the specific heat in the unit form kJ/m<sup>3</sup> K, which requires the above equation to use the volume flow ( $\dot{V}$ ) instead of the mass flow ( $\dot{m}$ ). There are no devices currently installed to measure the volume flow of the heated air, such measurement instrumentation cannot be installed without taking the plant out of operation and has not been done. The only source for the volume flow was from the studies conducted in 2011, in which the volume flow for the clinker cooler

gas was provided as an average value of 21,66 m<sup>3</sup>/s. The most recent study has been used with the volume flow assumed to be constant.

The annual heat lost through the cooler vent air was calculated using the specific heat for each time instance, combined with the fixed value for the volume flow and the available air temperatures. This approach incorporates the periods to which the kiln is offline. The sum of the heat lost for each hour provides for the amount in one year. The total annual heat lost from the gas is calculated using equation (3), with the average heat transfer rate obtained by dividing the total annual heat by the amount of hours in a year (the results for both can be found in Table 3).

$$Q_{cooler} = \dot{V} \cdot \sum_{i=1}^{8784} C_{p,i} \cdot (T_{gas} - T_{atm})_i \quad (3)$$

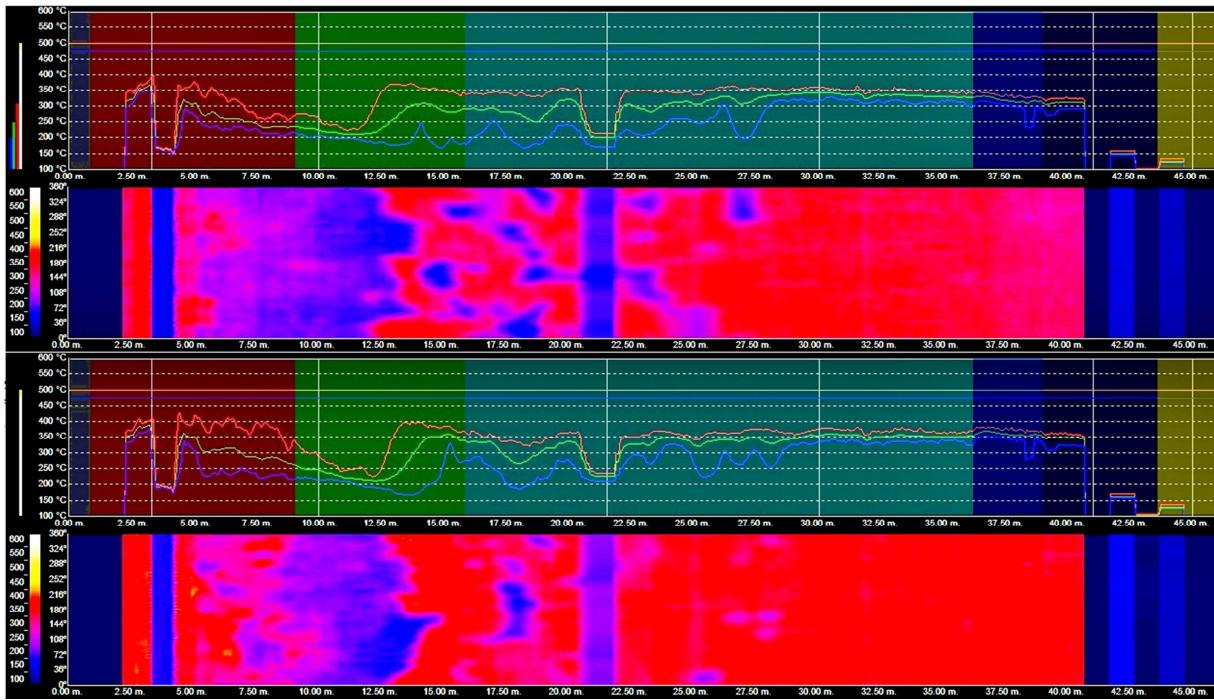
**Table 3 : The calculated annually available heat and average heat transfer rate for the clinker cooler gas.**

Heat	Average heat transfer rate	Total annual heat ( $Q_{cooler}$ )
Clinker cooler gas	5,78 MW	50,74 GWh/year

### **3.3.2.2 Kiln heat losses**

The largest significant losses are through radiation and convection from the outer shell surface, which is estimated from the 2011 studies to be between 8,3 MW and 9 MW (Stover, 2011). Heat is lost through both convection and radiation. The convection losses are from the forced air blasting of the shell, at the location between 0 and 20 meters, and the wind blowing across the entire shell, although the wind effect is the only effect considered during the calculations. The lost heat will be calculated separately for the convection and the radiation heat available from the shell surface.

It is known that the temperature of the surface is dependent on the type of fuel used, type of clinker manufactured, duration of operation from previous maintenance, atmospheric conditions, among other. The surface temperatures are monitored constantly by the plant control room. The student requested two printouts of normal operating conditions for the rotating kiln, as can be seen in Figure 8.

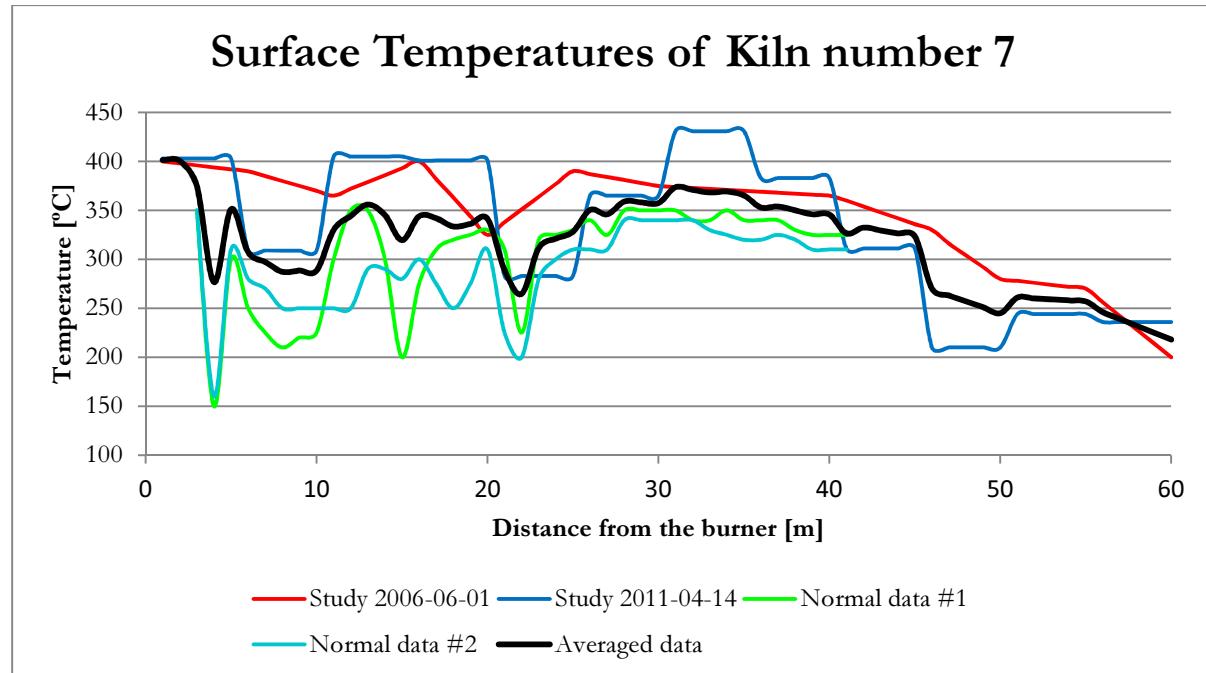


**Figure 8: Temperature graph with thermal image of the rotating kiln surface at two time instances.**

The surface temperature is influenced by various factors which causes the graphs in Figure 8. The red graph indicates the maximum temperature, blue the minimum temperature and the green the mean temperature at the specified distance over the entire circumference.

The surface area closest to the burner (on the left) is constantly being blasted with cold air, in order to generate a build-up of material on the inside. This creates the cooling effect which can be seen on the thermal image as blue marks. The temperature is not only affected by the build-up, but also from the method for controlling it. The burner flame is adjusted to burn with a broader or thinner flame, this together with the driver power adjustment will cause a significant and continuous change in the surface temperature. The last significant feature is the blue bands running vertically across the thermal images, these are caused by the “tyres”, described in the previous chapter.

The calculations were made difficult due to the lack of available surface temperature data. The temperature measurements in Figure 8 are only measured up to 40 meters of the 60 meter kiln. The available historical data and studies, with exclusion of “2011-10-19” due to insufficient data, were used to derive the shell temperature. The averages of the available measurements were used to estimate the temperature of the surface for each meter of kiln (see Figure 9).



**Figure 9: Measured surface temperatures for rotary kiln number 7.**

The first effect to calculate was the effect of convection. Although the town of Slite is prone to strong and constant winds, the wind speeds supplied by the weather service were not used. Following continual site visits during strong winds, it was clearly visible that the effect of the wind on kiln number 7 will be minimal. The kiln's outside surface area ( $A$ ) is largely sheltered by a concrete structure (see Figure 10), which together with the surrounding structures and abandoned equipment (kiln 6), protects it from the wind and other atmospheric conditions. Some wind does get through, although it is reduced significantly.



**Figure 10 : Kiln 7's sheltered position in its concrete structure.**

The temperatures used for the calculations were the average temperature (in Kelvin) of the kiln shell for each meter ( $T_s$ ), as well as the average atmospheric temperature ( $T_{av,atm}$ ). The convection heat transfer coefficient ( $\alpha_{conv}$ ) were approximated using the industry based calculation, and consequently convection losses ( $\dot{Q}_{conv}$ ) were could be calculated. According to the industry based calculation, the following requirements had to be met in order to use Equation (5): the wind speed is less than 2 m/s; the temperature in degrees Celsius ( $\vartheta_{kiln}$ ) is between 100 °C and 500 °C; the kiln diameter is between 2m and 8m; the atmospheric temperature is between 10 °C and 30 °C. (Kiln Performance Tests Task Force, 1992):

$$\dot{Q}_{conv} = \alpha_{conv} \cdot A \cdot (T_s - T_{av,atm}) \quad (4)$$

$$\alpha_{conv} = D \cdot 0,3 + 4 + 3,5 \cdot \frac{\vartheta_{kiln}}{100} - 0,85 \cdot \left(\frac{\vartheta_{kiln}}{100}\right)^2 + 0,076 \cdot \left(\frac{\vartheta_{kiln}}{100}\right)^3 \quad (5)$$

The convection heat transfer coefficient ranges between 12,65 W/m<sup>2</sup>.K and 26,09 W/m<sup>2</sup>.K, depending on the location on the kiln surface. These values correspond to the upper range of free convection of gasses (Çengel, 2003). The approximation (Equation (5)) is used throughout the cement industry with accuracy, it has therefore been assumed to be sufficient to use in these estimates.

By summing together the convection losses from each meter of kiln for different locations, and multiplying with the fraction of operating hours ( $n$ ) the kiln experience in a year, it is possible to derive an estimate for the yearly losses ( $Q_{kiln,conv}$ ) from convection.

$$Q_{kiln,conv} = n \cdot 8760h/year \cdot \sum_{j=1}^{60} \dot{Q}_{conv,j} \quad (6)$$

The next loss to calculate was the radiation loss from the kiln surface. The maximum rate of radiation ( $\dot{Q}_{emit}$ ) of a real surface that can be emitted from a surface at an absolute temperature ( $T_s$ ) is determined using the surface area, surface emissivity ( $\varepsilon$ ) and the Stefan-Boltzmann constant ( $\sigma$ ), as given by the Stefan-Boltzmann law (Çengel, 2003).

$$\dot{Q}_{emit} = \varepsilon \sigma A T_s^4 \quad (7)$$

$$\text{with: } \sigma = 5,67 \times 10^{-8} \left[ \frac{W}{m^2 K^4} \right]; A = L \times D \times \pi [m^2]; \varepsilon_{steel} = 0,9$$

In order to achieve an accurate estimate for the radiation, the heat available relative to the average atmospheric temperature ( $T_{av,atm}$ ) was used to calculate a new value for the radiation heat transfer ( $\dot{Q}_{rad}$ ). This equation was repeated for each meter of kiln, which was then summed together and multiplied by the availability ( $n$ ) and the hours in a year to obtain the heat lost due to radiation ( $Q_{kiln,rad}$ ) for the entire kiln in the period of one normal year. The total heat ( $Q_{kiln}$ ) can be calculated by summing together radiation and convection:

$$\dot{Q}_{rad} = \varepsilon \sigma A (T_s^4 - T_{av,atm}^4) \quad (8)$$

$$Q_{kiln,rad} = n \cdot 8760 \text{h/year} \cdot \sum_{j=1}^{60} \dot{Q}_{rad,j} \quad (9)$$

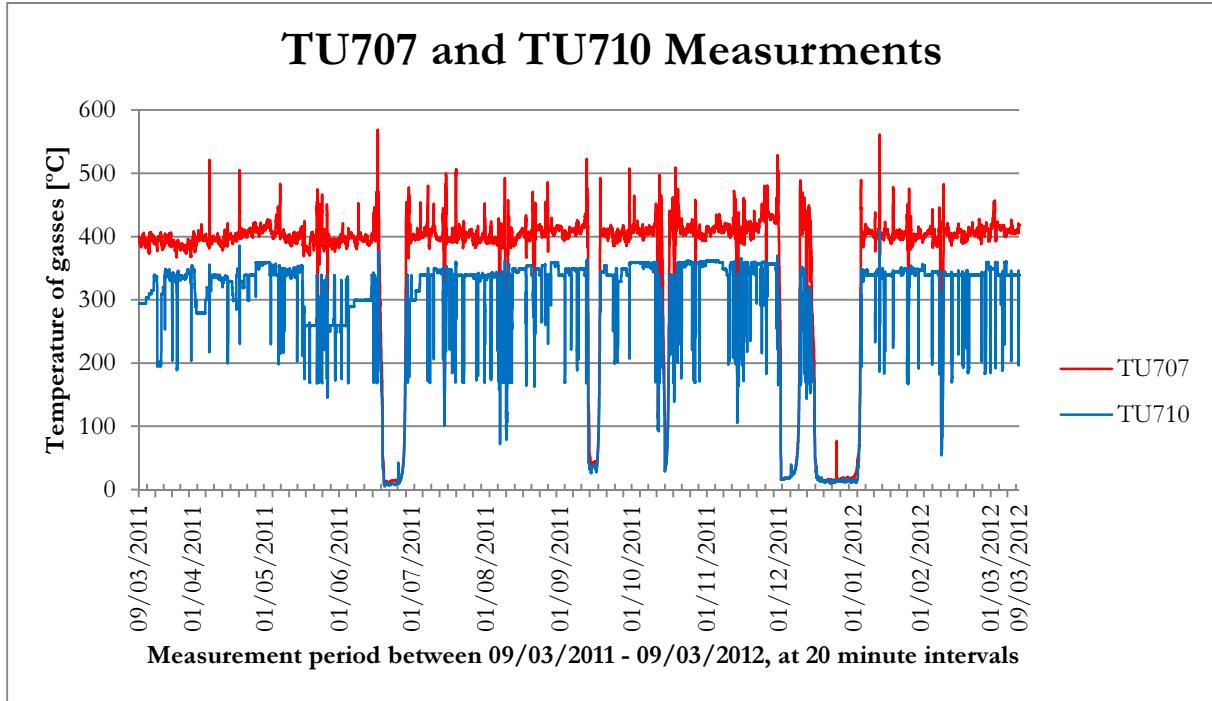
$$Q_{kiln} = Q_{kiln,conv} + Q_{kiln,rad} \quad (10)$$

**Table 4 : Heat losses from the kiln shell, relative to the atmosphere.**

	Availability	$Q_{kiln,conv}$	$Q_{kiln,rad}$	$\dot{Q}_{average}$	$Q_{kiln}$
Kiln shell	83,64 %	17,77 GWh/year	35,77 GWh/year	5,11 MW	44,78 GWh/year

### 3.3.2.3 Preheater raw gas

After the gas from the kiln has been used to preheat the raw meal, it is dissipated at the top of the cyclone tower to the cooling tower. The gas is then cooled before being sent to the raw mill. Some of the heat is used within the raw mill for drying, and therefore cannot be used without influencing an existing system. The temperature measurements can between the inlet (TU707) and outlet (TU710) of the cooling tower can be found seen in Figure 11.



**Figure 11:** Temperature measurements for sensor TU707 and TU710 over a one year period.

In order to ensure minimal influence on the operation, yet obtain some measure of energy from the gas, the amount of energy dissipated by the cooling tower was considered a possible source. The cooling tower

works by cooling down the gasses through injecting water directly into the gas. This causes a change in the mass flow and the energy content of the gas.

In order to access the heat through a heat exchanger, the air will have to be diverted from the cooling tower. The effect of this is the removal of the water added by the cooling tower. It has been requested that the amount of energy contained in the gas after the cooling tower should remain the same, after modifications to the system, due to the requirements of the rawmill further downstream. It is therefore necessary to first calculate the energy after the water tower, in order to establish the required outlet conditions of the heat exchanger. The gas exiting the new heat exchanger should have the same amount of energy as the cooling tower exit gas, although at a different mass flow rate.

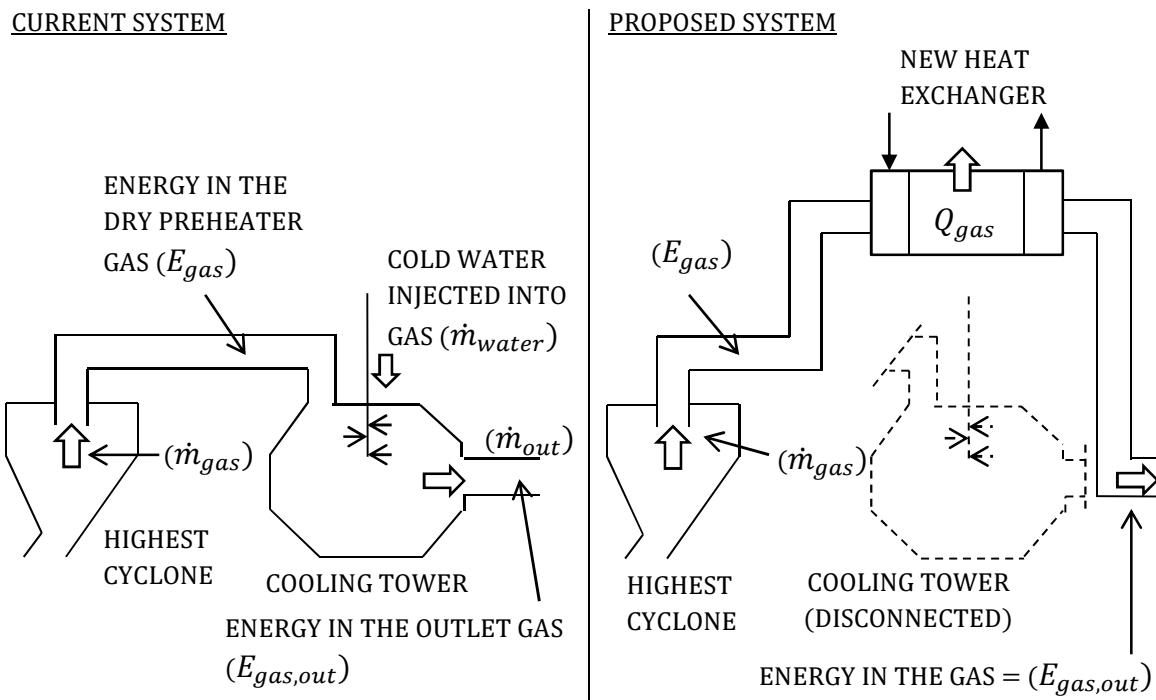


Figure 12 : Current and proposed preheater gas outlet, before the raw mill.

The difference between the cooling tower gas's in- and outlet conditions, allowed for the calculation of the available energy ( $E_{available}$ ) that can be removed using a heat exchanger.

$$E_{available} = E_{gas} - E_{gas,out} \quad (11)$$

The energy into the cooling tower through the dry gas ( $E_{gas}$ ) was calculated using the industry guide (Kiln Performance Tests Task Force, 1992), with the given concentrations based on the previously conducted studies. The energy out of the cooler ( $E_{gas,out}$ ) was calculated using the same equations, but for a different concentration and temperature values, due to the added water.

The specific thermal capacity ( $C_{p,gas}$ ) of the gas leaving the preheater, calculated in J/K.m<sup>3</sup>, can be estimated as the sum of the individual particles (CO<sub>2</sub>, H<sub>2</sub>O, O<sub>2</sub>, N<sub>2</sub>) multiplied by their volume fraction ( $\chi$ ) in the gas, obtained from the 2011 studies and listed in Table 5. The thermal capacity of the particles was estimated using the gas temperatures ( $\vartheta$ ) in °C, as per the formulas provided by the available guidelines. (Kiln Performance Tests Task Force, 1992)

$$C_{p,CO_2} = 1,633 + 9,631 \cdot 10^{-4} \cdot \vartheta - 4,606 \cdot 10^{-7} \cdot \vartheta^2 + 8,9 \cdot 10^{-11} \cdot \vartheta^3 \quad (12)$$

$$C_{p,H_2O} = 1,489 + 9,52 \cdot 10^{-5} \cdot \vartheta + 2,021 \cdot 10^{-7} \cdot \vartheta^2 + 7,35 \cdot 10^{-11} \cdot \vartheta^3 \quad (13)$$

$$C_{p,N_2} = 1,301 + 3,05 \cdot 10^{-5} \cdot \vartheta + 9,65 \cdot 10^{-8} \cdot \vartheta^2 - 3,22 \cdot 10^{-11} \cdot \vartheta^3 \quad (14)$$

$$C_{p,O_2} = 1,304 + 1,916 \cdot 10^{-4} \cdot \vartheta - 9,4 \cdot 10^{-9} \cdot \vartheta^2 - 1,01 \cdot 10^{-11} \cdot \vartheta^3 \quad (15)$$

$$C_{p,gas} = \sum_{k=CO_2;H_2O;N_2;O_2} C_{p,k} \cdot \chi_k \quad (16)$$

**Table 5 : The volume fraction of the molecules in the gas before the cooling tower.**

Particle	CO <sub>2</sub>	H <sub>2</sub> O	O <sub>2</sub>	N <sub>2</sub>
Volume fraction ( $\chi$ )	0,2355	0,0910	0,0388	0,6350

The specific thermal capacity together with the fixed volume flow ( $\dot{V}$ ) from the 2011 study and the measured exit temperatures ( $T_{TU707}$ ) in Kelvin, allowed for the calculation of the energy of the gas ( $E_{gas}$ ) before the cooling tower. Repeating this equation for every measured hour in the year and summing it together, provides for the total energy in one year.

$$E_{gas} = \dot{V} \cdot \sum_{l=1}^{8784} C_{p,gas,l} \cdot T_{TU707,l} \quad (17)$$

In order to calculate the energy in the gas after the cooling tower ( $E_{gas,out}$ ), the mass flow added to the system by the water sprinklers ( $\dot{m}_{water}$ ) had to be added to the mass flow of the gas ( $\dot{m}_{gas}$ ) from measurements. Volume flow change caused by the cooling tower is calculated using the mass flow of the gas ( $\dot{m}_{gas}$ ) together with the mass flow added by the water ( $\dot{m}_{water}$ ).

$$\dot{m}_{out} = \dot{m}_{gas} + \dot{m}_{water} \quad (18)$$

The gas mass flow was derived from the assumed volume flow ( $\dot{V}_{gas}$ ) before the cooling tower, times the concentration ( $\chi$ ) of the gas and the density at the given temperature.

$$\dot{m}_{gas} = \dot{V}_{gas} \cdot \left[ \sum_{m=CO_2;H_2O;N_2;O_2} \rho_m \cdot \chi_m \right] \quad (19)$$

The density of the water added ( $\rho_{H2O}$ ) was obtained from the saturated water condition at the average water temperature of about 16 °C, before injection into the gas. The volume flow of water was obtained from the difference between the measured volume flow before the exit nozzle ( $\dot{V}_{FU711}$ ) and after the exit nozzle ( $\dot{V}_{FU710}$ ).

$$\dot{m}_{water} = \rho_{H2O} \cdot (\dot{V}_{FU711} - \dot{V}_{FU710}) \quad (20)$$

The new volume flow of the gas with water vapour leaving the cooling tower ( $\dot{V}_{out}$ ) was calculated in order to use together with the specific heat to determine the energy at the output. It was calculated using the cooling tower outlet mass flow ( $\dot{m}_{out}$ ) with the concentration of molecules from the inlet conditions calculated to include the added water molecules from the sprinkler and the density of each molecule obtained from EES software, calculated for the average measured gas temperature on the outlet. The concentration change caused by the added water required the calculation of a new concentration ratio after the cooling tower, as can be seen in Table 6.

**Table 6 : The volume fraction of the molecules in the gas after water injection.**

Particle	CO <sub>2</sub>	H <sub>2</sub> O	O <sub>2</sub>	N <sub>2</sub>
Volume fraction ( $x$ )	0,2263	0,1264	0,0373	0,6101

Each of the molecule's densities and concentrations were multiplied separately and then summed together for calculating the outlet volume flow.

$$\dot{V}_{out} = \dot{m}_{out} / \left[ \sum_{m=CO_2;H_2O;N_2;O_2} \rho_m \cdot x_m \right] \quad (21)$$

The measured temperatures allowed for new specific thermal capacity values ( $C_{p,out}$ ) to be calculated using standard equation used previously. Using these values the energy inside the gas at the exit of the cooling tower were calculated.

$$E_{out} = \dot{V}_{out} \cdot \sum_{n=1}^{8784} C_{p,out,n} \cdot T_{TU710,n} \quad (22)$$

The heat lost was obtained as the difference between the energy before and after the heat exchanger. The rate of heat transfer was estimated using the heat lost divided by the hours of the year.

$$Q_{gas} = E_{available} = E_{gas} - E_{out} \quad (23)$$

**Table 7 : Energy, annual and average heat transfer rate of the preheater cyclone gas.**

	$E_{gas}$	$E_{out}$	Heat transfer rate	$Q_{gas}$
Pre heater gas	236,54 GWh/year	200,29 GWh/year	4,1 MW	36,18 GWh/year

### **3.3.3 Discussion of results**

The heat values have been calculated using historical measurements obtained from the period stretching from March 2011 to March 2012. These values indicates the heat lost from the clinker cooler gas, heat from the preheater gas lost through the cooling tower and the heat lost through convection and radiation from the kiln shell. All of the energy sources are discussed further, comparing the results with the most recent system audit, “2011-10-19”.

The values differ from the previously conducted system audits. Many reasons could be associated with this difference, of which the most important relates to the method of calculation. Lower values are expected form the calculated results due to the calculation of the average heat lost, which includes the offline periods, resulting from an operating period of 83,64 % for one year. The system audits were only calculated for a specific two day period, using the conditions of that period only. Additionally, other differences related to the assumptions made were also identified for each source.

The heat available from the clinker cooler gas was calculated using the same methods used during the system audit. The average rate of heat loss were calculated to be 5,77 MW, which is less than the 7,71 MW obtained in the audits. Part of the reason could be associated to the change in atmospheric temperatures that occur throughout the year, which was not taken into account by the audits.

The kiln shell radiation and convection losses also used the same calculation methods as per the audit, but with different assumptions. The calculated heat loss of 5,11 MW is less than the 8,99 MW obtained from the audit. Assumptions made with respect to the environmental conditions are assumed to be largely responsible for this difference. The audit assumed high average wind speed conditions over kiln number 7, over 2 m/s, as measured by the weather station in the region. Under closer investigation, these assumptions were found to be inaccurate. Kiln number 7 is enclosed to a large extent. The entire kiln is located inside a large partially closed concrete structure with a roof. Additionally, the North facing side of the kiln is sheltered by the unused kiln number 6 and workshop buildings further away. After visiting on site during strong winds and winter conditions, it was found that the kiln is very well protected from the outside environment. The new, lower wind speed assumptions were therefore assumed, reducing the calculated convection losses.

The preheater gas calculations were much different from the audits, due to the presence and inclusion of the cooling tower. The audits only calculated the heat in the exit gas, not taking into account that a large amount of gas and heat is used by the raw mill further down the line. The newly calculated values takes this into account, delivering a lower heat loss rate of 4,12 MW, compared to the audit’s 13,87 MW. Even with the large reduction, the preheater gas is still considered one of the three largest sources of lost heat.

The newly calculated values were assumed to be much more accurate for use in this study, due to reasons explained above. The largest source of heat loss is considered to be the kiln shell, with the clinker cooler gas being a close second with a lower temperature range. The preheater gas is the lowest source of heat

loss, but at the highest temperature range. The results are considered sufficient to use for further analyses, which explores the possible connections and methods for capturing the heat.

**Table 8: Summary of the results from the three largest heat sources.**

Energy Source	Heat transfer type	Average temperature	Average Heat lost	Annual heat lost
Clinker cooler gas	Convection	212,5 °C	5,78 MW	50,74 GWh/year
	Radiation	322,7 °C	3,42 MW	35,77 GWh/year
Kiln shell	Convection		1,69 MW	17,77 GWh/year
Preheater gas	Convection	355,8 °C	4,12 MW	36,18 GWh/year
Total			15,01 MW	140,46 GWh/year

## **3.4 Using the heat**

The intention was to evaluate the possible heat sources and determine the most effective use for each source. The setup between the possible use and the source is considered and effective use of heat when it is recovered and uses the highest amount of heat at the smallest capital cost and highest financial savings possible, the relation determined through the payback period, in a practical and realistic way.

With the three possible sources established in the previous section, this chapter aims at establishing the uses and comparing the calculated heat recovery and costs of each source. The uses were limited to what is available on site, taking into account that the processes used for cement manufacturing should not be influenced.

Inclusion of the existing district heating and electrical system found at kiln number 8 was of great importance to Cementa AB. The existing setup has therefore been discussed and evaluated in order to determine possible ways to which kiln number 7 can improve these systems.

Such an evaluation allowed for the identification of the most feasible connection, through comparing each use connected to each source. It was decided to only evaluate one connection per source, causing the final result to contain the most feasible connection to each of the three sources. The chosen setups could then be evaluated in more detail and discussed further in the final chapter.

### **3.4.1 Existing equipment for new connections**

The first heat recovery project involved the district heating connection to the clinker cooler gas outlet at kiln number 8. The second heat recovery project involved connecting a steam turbine to an economizer and boiler at the clinker cooler outlet, and a boiler and superheater to the preheater gas outlet.

The clinker cooler gas had to supply heat to two different systems at the same time. The disadvantage of this setup is that, during winter months, the demand for district heating and electricity is very high. The consequence is that the system is not large enough to meet the demand of both, with most of the heat being diverted to the district heating.

To meet the demand of the district heating, oil burners are used to heat up the water, elimination of these burners will be beneficial, environmentally and economically, to the company. The opportunity therefore exists for connecting the district heating to the new kiln number 7 system, which would allow the elimination of the oil burners at kiln number 8. This is achieved by analysing each heat exchanger and discussing the possible improvements from kiln 7.

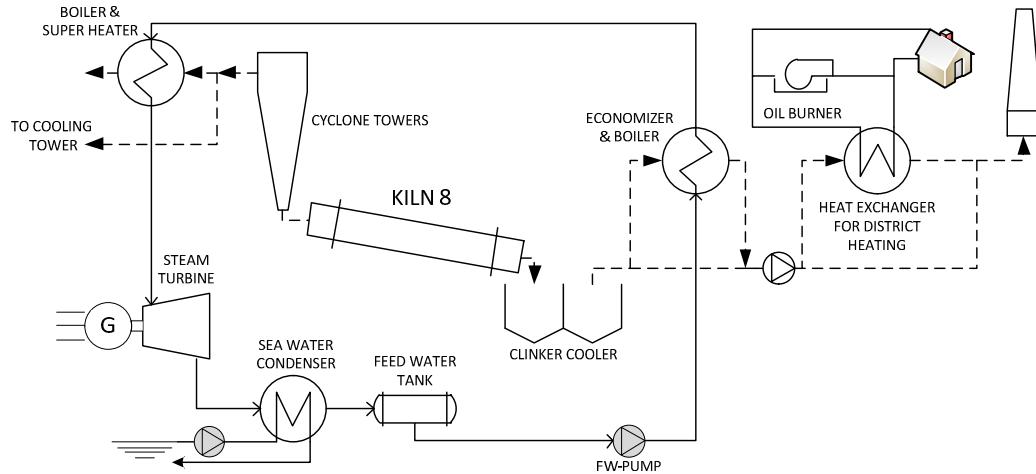


Figure 13: Simplified diagram of kiln 8, showing steam turbine and district heating connections.

### 3.4.1.1 Electrical generation

The existing electrical generation system is connected to kiln number 8, and was completed in 2001. Water is heated in an economizer and boiled in a boiler which connects to the clinker cooler gas outlet. The steam generated is transferred to the second boiler, connected to the raw gas outlet on top of the cyclone tower. The steam is superheated to the desired temperature and then pumped to the steam turbine in order to generate electricity to the grid.

Since its completion, the system has been unable to deliver on the design values, as can be seen in Table 9. The information derived from the measured results indicates that the mass flow of steam is much lower than the designed value. The causes of this had to be identified before attempting to connect to the system from kiln number 7. After closer investigation and discussion with the operators, the following was found:

- The heat exchanger's heat transfer capabilities are much lower than initially calculated.
- The low mass flow of the steam is a consequence of the reduced steam production.
- The turbine capability is 15 MW, therefore much higher than designed for.
- The pump capacity is also much higher than the given design values.
- The current control system is optimized for working under the lower conditions.

This reveals that the possibility exists for kiln number 7's heat to be used in order to improve the existing system. How it should be used can be investigated by discussing the current operation and setup of each heat exchanger.

Table 9 : Design and historical conditions of the existing electricity generating system.

	Unit	12 May 2003	Average 2011	Maximum recorded power 2011	Design conditions
Electrical generation	(MW)	5	4,87	7,17	8,8
Heat Exchanger 1	(MW)	15	19,5	21,8	20
Heat Exchanger 2	(MW)	3,5	3,63	5,9	10
Mass flow (steam)	(kg/s)	6,7	6,56	10	11,3
Pressure before turbine	(bar)	30,1	26	26	35
Temperature before turbine	(°C)	396	400	373	380
Temperature after turbine	(°C)	110	108	108	120

### 3.4.1.2 Heat exchanger 1 description

Heat exchanger 1 (HE-1) is a cross flow heat exchanger located at the preheater cyclone's raw gas exit, above the cyclone tower, and consists of a boiler and a super-heater. The heat exchanger receives two inlets merge together, one for each cyclone tower for the kiln, which will be modelled as one. The heat exchanger removes the heat from the raw gas, reducing the cooling requirement of the cooling towers and also using the heat to generate steam used by the steam turbine.

The hot gasses from the cyclone tower are forced through the heat exchanger, transferring the heat to the boiler and superheater. Depending on the conditions at HE-2, either water or steam is transferred to the steam drum. The water and steam are separated and used for different functions. The water is pumped from the bottom of the steam drum through the boiler, which generates more steam. The steam is taken from the steam drum and superheated by the superheater, located in front of the boiler, in order to access the higher gas temperatures. The superheated steam is then pumped to the steam turbine for electricity generation (see Figure 14).

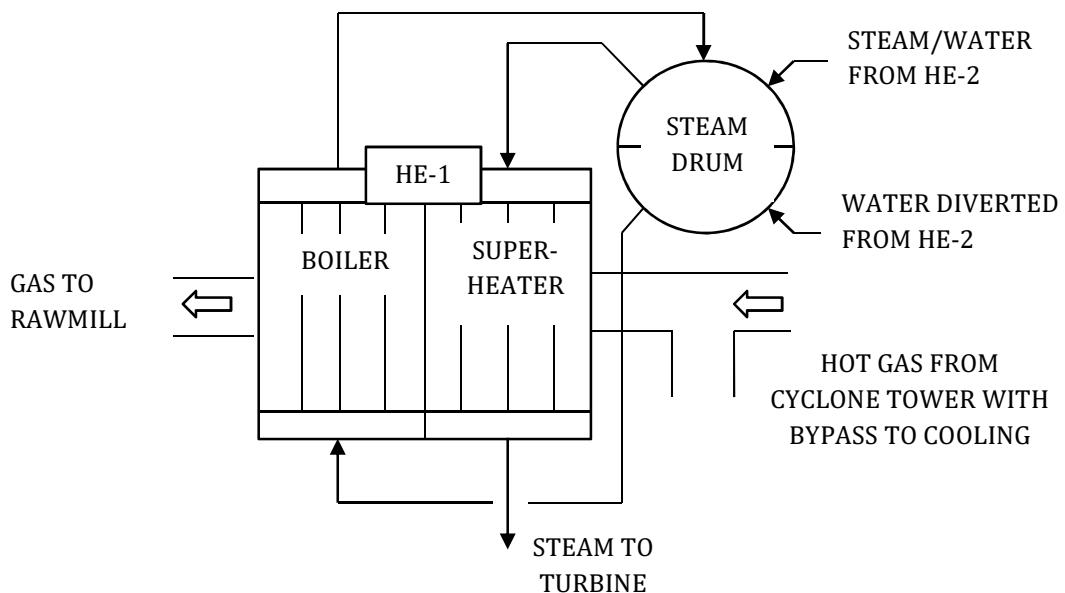
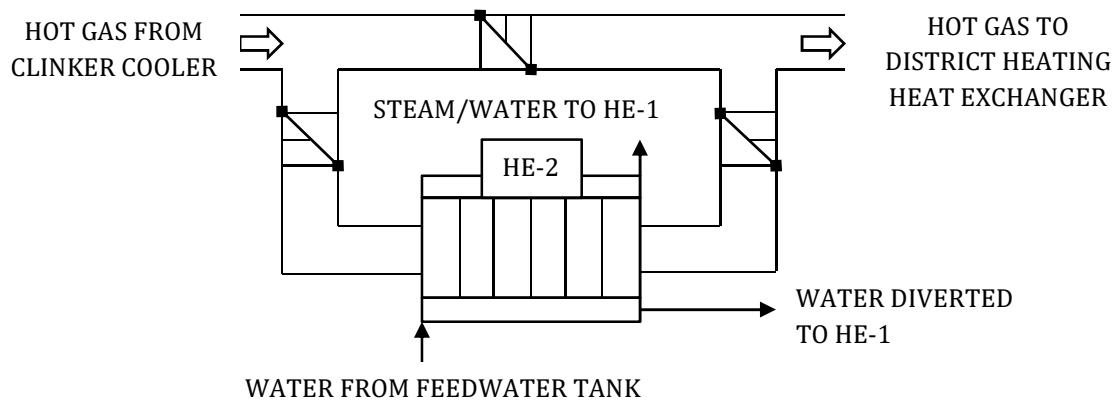


Figure 14 : Layout of heat exchanger 1 and connections.

The low efficiency of HE-1 creates the effect that the temperature of the gas leaving to the raw mill is much too high for the rawmill. It is therefore required to divert some of the hot gasses to the cooling towers. The towers spray cold water into the gas, which cools it down, before connecting up to the rest of the vented gas for transportation to the rawmill. Lower steam production from HE-2, together with low steam production at HE-1, reduces the mass flow of the steam and also the heat transfer efficiency in HE-1. The less heat transferred the more cooling required and the more energy used and wasted through water cooling in the cooling towers.

### **3.4.1.3 Heat exchanger 2 description**

Heat exchanger 2 (HE-2) is a shell tube heat exchanger consisting of an economizer and boiler. The first of two heat exchangers connected to the clinker cooler gas outlet. There is a bypass system installed around the heat exchanger, this allows for diversion of the hot gasses to the second heat exchanger, used by the district heating system (see Figure 15).



**Figure 15 : Layout of heat exchanger 2 and connections.**

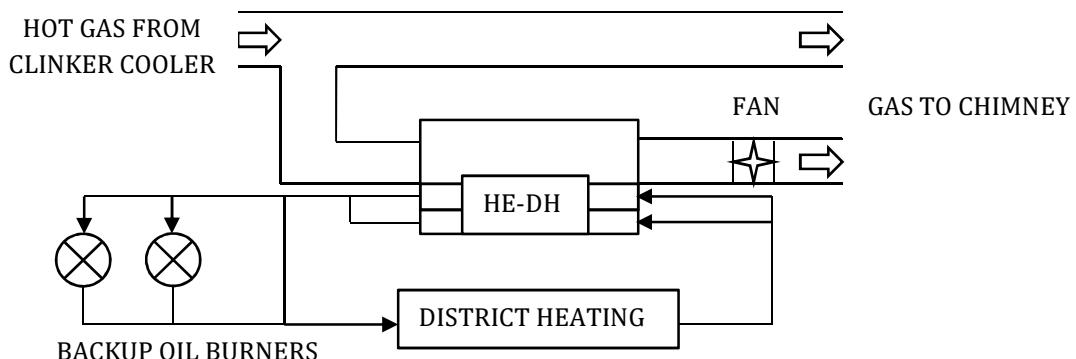
This heat exchanger is considered second priority in the system. When the demand for district heating is high, the control vents are manually closed and the hot gas is bypassed to the district heating heat exchanger. The system is designed such that when the temperature of the water inside the heat exchanger is reduced to less than 240 °C, it is redirected directly to HE-1.

The reduced heat transfer rate of HE-2 caused the operators to reduce the pressure of the water entering the system. The reduced pressure will have the effect of reducing the temperature required for generating steam, increasing the steam mass flow. During winter months the colder temperature requires less air for cooling the gas, this reduces the waste heat gasses, which in effect reduce the heat transfer even more and consequently the electrical production.

### **3.4.1.4 Heat exchanger for district-heating description**

The district heating heat exchanger (HE-DH) uses a shell tube cross flow heat exchanger, which heats the district heating water to a relatively low heat compared to the previously discussed heat exchangers. Water used for district heating is directly heated using the clinker cooler outlet gasses. The heat exchanger also has a bypass system for venting to the cooling tower, in case the demand is too low or temperature too high.

This heat exchanger is considered first priority for heat. This is due to the requirements of the district heating system, which does not allow for interruptions in the heat supply. To prevent interruptions two additional oil burners are connected in parallel to the system, as can be seen in Figure 16. As soon as the temperature drop, one of these oil burners will be activated, if the temperature continues dropping, the second one will also be activated. The reduction of this oil consumption is the reason for prioritizing the heat exchanger. The operations use a rule of thumb, which states that the burning of oil will not occur unless the temperature of the gas drops below 176 °C, when this happens, the operator will manually activate the oil burners.



**Figure 16 : Layout of heat exchanger for district heating, and connections.**

Demand is at a peak in winter time, when the least amount of heated gas is available. The gas is therefore diverted from electricity generation to the district heating in order to prevent the burning of oil. With these attempts the oil consumption is still very high, 400 m<sup>3</sup> for 2011. Oil is mostly consumed during a shutdown of kiln number 8, which stops the flow of hot gasses and maximizes the dependence on oil.

### **3.4.2 Financial benefits**

In order for the heat sources to become feasible, it has to provide a form of financial savings or gains. Due to limitations, no additional infrastructure can be installed to increase on the possible gains that could be made. As a consequence, most benefits are in the form of savings. There was one source of financial

gains through electricity certificates supplied each year, which inevitably changed due to a change in regulations.

The improved generation of electricity will reduce the amount of electricity to be purchased, resulting in financial savings based on the electricity savings. This is made more complicated by the relationship between the companies, but will be discussed further in the next section.

The district heating is limited to the demand, as a consequence no additional earnings could be made. Any savings related to the district heating would be the reduction of the oil burned and electricity saved through reducing the bypassing of HE-2. The financial savings would be from the reduced costs due to the reduction in oil purchases and the reduced cost through electricity savings.

### **3.4.2.1    *Electricity***

Cementa AB, together with Vattenfall AB, worked on connecting kiln 8 with the steam turbine. In this partnership, a specific cost sharing relationship was established. Both companies paid for the capital costs of the equipment. Vattenfall is the owner of the equipment, including HE-1 and HE-2, and is responsible for managing and maintaining it. Cementa AB supplies the steam to the turbine for no costs, although the contract intended to provide Cementa AB with the benefit of lower electricity rates for the electricity generated by the turbine, this does not always occur.

When this report was written, Cementa AB and Vattenfall were to have a discussion to relook at the contract. One of the possible outcomes was that Cementa AB buys out the equipment and responsibility from Vattenfall, which would benefit Cementa AB directly.

This report considered the scenario of Cementa AB being the owner of the turbine system. With costs related to the operation and maintenance of the equipment, already incurred. This assumption allowed for each kWh of electricity recovered or improved by the new system to be a direct cost benefit relative to the average paid price for buying electricity. The cost of electricity in 2011 was at 520 SEK per MWh, which would be used in all the calculations related to electricity gains.

### **3.4.2.2    *District heat***

Another partnership undertaken by Cementa AB is one with GEAB related to the supply of district heating. The Cementa AB plant in Slite, is the only source of district heating in the area. The heat is supplied largely to the local ice rink and the local greenhouse. The two companies shared the cost of installing a heat exchanger at kiln number 8 and have developed a contractual agreement for the sharing of profits.

GEAB is the owner of the equipment, and is responsible for the management and maintenance thereof. The only backup is the oil burners mentioned in previous sections. The agreement stated that all profits made from district heating are shared 50/50 between the two companies. The effect was that for each

kWh saving incurred by the new system, 50 % of the savings will benefit Cementa AB. The reduction in oil burning will therefore translate to a cost saving to both companies, divided equally between them.

The type of oil burned was stated by Cementa AB to be mixed diesel oil, which was rated at a cost of 7 000 SEK per cubic meter. For each kroner saved, half of the savings will be incurred by the company in the calculations that follows in the next section.

### **3.4.2.3 Regulations and certificates**

The Swedish energy authority (Energi Myndigheten) currently operates a certificate scheme, in which certificates are provided to electricity suppliers who choose to use biomass based fuels (biofuel). In previous years Cementa AB was able to benefit from this scheme. This changed when Energi Myndigheten changed the policy.

In December 2011, the Swedish authorities released an amendment (SFS 2011:1480) to the regulations surrounding the issuing of electricity certificates (“elcertifikat”). The new amendment revised the definition for “Biofuels”. The new definition excludes unsorted waste, irrelevant of the content, from being classified as biofuel . If the fuel is sourced in a mixed state, such as the case for Cementa AB, they do not qualify for the certificate.

The Swedish environmental protection agency (Naturvårdsverket) has a different definition for the term “biomass fuel” which would allow Cementa AB to qualify for a certificate. The regulation has the potential to change, due to conflicting definitions between the two departments, which would allow for additional benefit for Cementa AB. Although this possibility exists, it is currently not in favour of the company and it was therefore not considered for this report. The estimated benefit for 2011 was 1 million Swedish krona (SEK).

### **3.4.3 Availability**

Connections to other systems and the benefits derived therefrom are dependent on the availability of both sources. If the shutdown times of two interconnected and interdependent systems occur at different durations, the output of the product will be reduced greatly, irrespective of the magnitude of the outputs. The contrary is also possible, for two interconnected but independent systems, the output can be improved. In order to account for this, the operational period for each connection has been estimated and included in the calculations.

In the case of connecting to the existing electrical system using kiln 7, the contribution from kiln 7 will be limited to the availability of the electrical system. Thus, kiln 7 can only contribute to the electrical system if kiln 8 is operational and the turbine is generating electricity. Kiln 7 will only be able to contribute heat if its temperature exceeds the temperature requirement of the steam or water. The contribution of a specific setup was therefore estimated by comparing the data for each hour for the duration of one year, the sum

of the yearly data incorporates the availability into the equation. In cases where the data for each hour is not available, average values had to be used and the availability had to be estimated as a percentage value.

The percentage availability for electricity generation was calculated by using the temperature of the source ( $T_{source}$ ) from kiln 7 at a point in time ( $\tau$ ) (hourly values for the year), minus the temperature required ( $T_{req}$ ) for contribution (such as steam or water temperature). This value will be aligned with the availability of kiln 8, through its measured gas temperature ( $T_{k8}$ ) minus arbitrary lower temperature for the same time instance. If both deliver positive results, contribution to the system will take place at that time instance. The percentage availability ( $\tau_{on}$ ) of the connection is calculated as the total amount of hours available to contribution divided by the total amount of hours in a year.

$$\text{if } (T_{source} - T_{req}) > 0 \text{ and } (T_{k8} - T_{req}) > 0, \\ x(\tau) = 1, \text{else } x(\tau) = 0 \quad (24)$$

$$A = \sum_{\tau=1}^{8784} x(\tau); B = 8784 \text{ h/year} \quad (25)$$

$$\tau_{on} = \frac{A}{B} \cdot 100 \% \quad (26)$$

The opposite approach is true for the district heating. The district heating system is dependent on any source of heat, therefore if the kilns are not operational, another source is required, such as oil. Kiln 7 can be connected as the primary source of heat, with kiln 8 as the secondary and the oil burners as tertiary sources. Such a connection will free up more heat for kiln 8 to use for electricity generation and less oil will be burned. The availability was not calculated as above, instead it was included in the energy calculations for each time step.

### **3.4.4 Calculating the heat transfer rates**

The two largest sources of heat loss have been found to be from the gas outlets and the kiln shell. The gas outlets will rely on convection heat transfer, while the kiln shell will rely on radiation and convection heat transfer.

For convection heat transfer, various heat exchangers and dedicated manufacturers and suppliers exist. The science behind its design is much more established and this chapter will not go into the details thereof. The specifications for the specific operating requirements will be stated with a discussion on the existing heat exchangers.

Radiation based heat exchangers are more academic with less industrially available options. The possibility of using tubes and concentrators has been investigated using basic analyses tools. An approach using a secondary shell with tubes as a form of heat recovery from the kiln shell has been investigated in other studies. The data and properties surrounding this technology have been estimated from previous studies, and are described in more detail.

The heat transfer capabilities provides for a good estimate for the amount of heat that can be obtained. A more accurate estimation can be made for each source, allowing for comparisons to establish the best heat recovery.

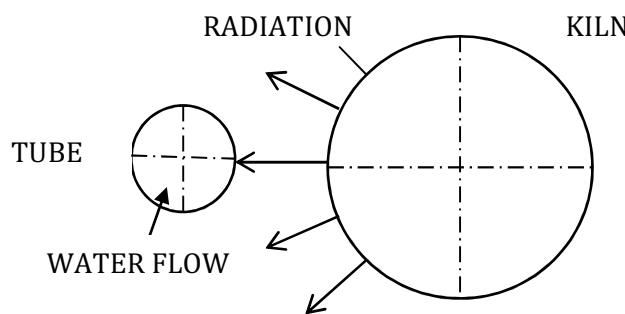
### **3.4.4.1    *Capturing heat from kiln surface***

Radiation can be captured through the presence of a collector surface within proximity from the kiln surface. Various equipment exist for this function in other industries, such as solar collectors, and some still under investigation, such as a secondary shell for the kiln.

Solar thermal technology specializes in the capturing the radiation heat of the sun for heating a liquid. For most solar energy application, only thermal radiation is important (Duffie & Beckman, 1991). In theory the radiation of the kiln can replace the radiation obtained from the sun to support the same function. Borrowing from the basic concept, the student investigated possible collector tubes and concentrating reflectors. The comparison of these solutions has been kept simple to merely get an estimate. Cost estimation was based purely on equipment costs, with heat transfer and savings based on published papers.

#### **3.4.4.1.1   Solar design considerations**

In order to investigate a lower cost simpler solution, the student first investigated the effects on a single tube running parallel to the kiln shell (Figure 17) and its heat absorption capabilities. The water inside the tube will gain heat through radiation from the kiln shell, but also loose heat through radiation and convection to the environment. This method did not prove to be feasible and the calculations have therefore been added to the appendix.

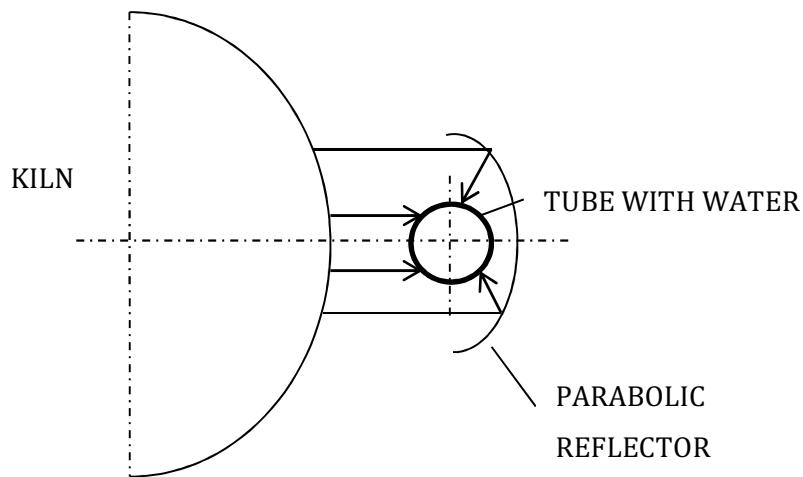


**Figure 17 : Single tube proximity approach.**

It was clear that the larger the tube, the more energy per unit cost is achieved, peaking with the 100mm pipe. The use of fewer larger tubes was found to be a slightly more cost effective approach than using many smaller tubes. The temperatures were within a small margin of difference, increasing slightly with

increasing pipe size. The losses can be significant, but can also be reduced through insulating the unexposed section of the pipe.

Secondly the student intended to improve on the above setup, by borrowing an idea from solar power. It is possible to improve the radiation exposure on the tube by concentrating more radiation onto it (Figure 18). The exposed area will thereby increase and consequently the radiation heat transfer. Such exposure requires a highly reflective surface, to reflect the radiation onto the tube. By enclosing the tube, additional convection and radiation losses are reduced or even eliminated.

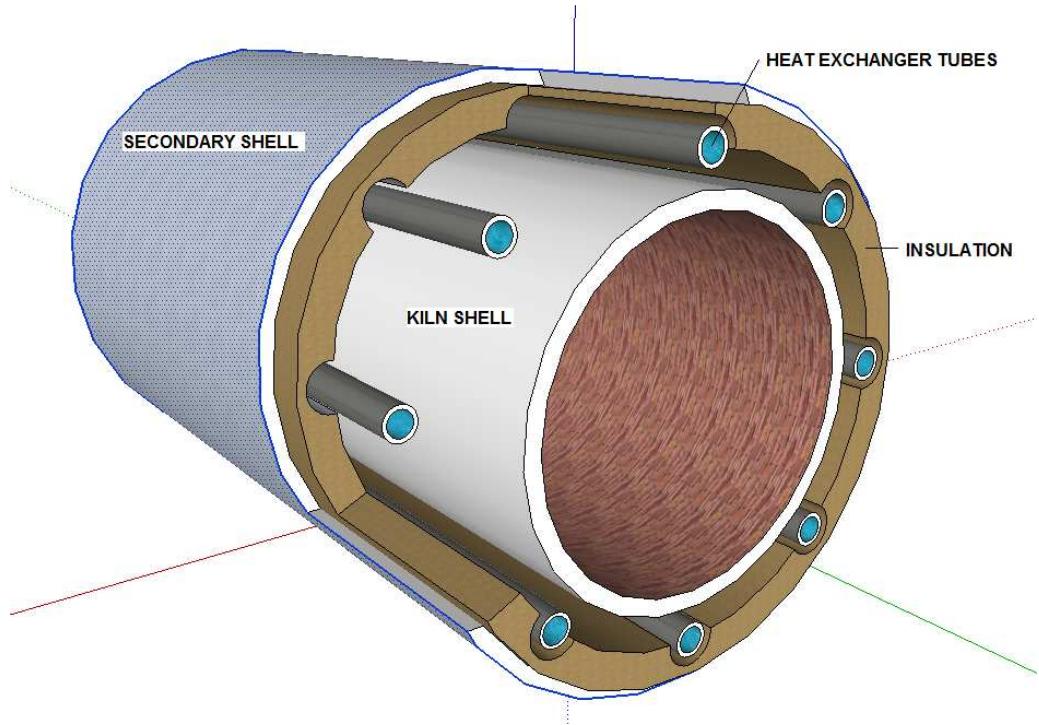


**Figure 18 : Concentrator and tube approach.**

The concentrator added increased radiation heat to the tube. With increasing reflector size and increasing tube size, the transfer increased, unfortunately the cost also. The cost of a reflector proved to be very high and the setup in itself became unfeasible economically.

#### 3.4.4.1.2 Secondary shell with tubes

A proposed solution is the secondary shell solution (Tahsin & Vedat, 2005). The secondary steel shell envelopes the kiln within a close distance from its surface, a layer of insulation with reflective surface can be found on the inside to reduce the heat transfer to the outside. Between the insulation and the kiln surface heat exchanging tubes can be found.



**Figure 19: Illustration of possible secondary shell with tubes setup (not to scale).**

The given setup not only reduces lost heat from radiation, it has the added benefit of reducing the heat lost due to convection (Tahsin & Vedat, 2005). The amount reduced heat will depend on the area covered and also the heat transfer capability.

The secondary shell will have to conform to some basic and specific requirements of the cement plant in Slite: surface contact should be avoided to prevent additional heat transfer from the kiln (Sögüt et al., 2010); the operator's capabilities to measure the surface temperature via the existing system should not be affected.

It is estimated that a secondary shell and tube system can recover about 73 % ( $\eta$ ) of waste heat from the shell (Sögüt et al., 2010). The average heat ( $\dot{Q}_{kiln}$ ) of the kiln shell calculated previously will be used for the estimation purposes, divided by the length of the kiln ( $L_{kiln}$ ), which can be compared to the estimate cost per meter of the kiln.

$$Q = \frac{\dot{Q}_{kiln} \cdot \eta}{L_{kiln}} \quad (27)$$

A fully enclosed setup can only be used in the area not currently monitored by the operations department. The only such area that exists, are within the distance of 40 meters and 60 meters from the burner. The temperature at this region is also much lower than the rest of the kiln and a correction of 0,93 had to be added to the above equation to account for the average differentiation.

The restriction mentioned above, has the possibility to be overcome through correct design of the kiln shell. Estimation will also be made for the covering of the entire shell, assuming that all the operational requirements can be met.

The cost is a combination of the cost of pipes, large flat steel plate to be used as the shell, insulation and reflective lining. An installation cost estimate, together with the cost of support has been provided by one of the experienced consultants on site. The estimates supplied by him are considered more accurate than any estimation the student could make, due to the experience and knowledge the consultant has within the field.

The secondary shell heat exchanger poses an interesting result, Table 10, even though it is a tried and tested type of heat exchanger. It will be considered as the only radiation heat exchanger to be used and included in the calculations that follows. It has a size limitation which will limit its contribution

**Table 10 : Heat recovery of secondary kiln shell.**

Maximum length	Cost of Equipment	Average Heat	Recovered Heat	Water Temperature
Part length – 20 m	4 786 k.SEK	0,98 MW	8,57 GWh/year	300 °C
Full length – 60 m	14 358 k.SEK	5,11 MW	32,69 GWh/year	300 °C

### **3.4.4.2    *Capturing heat from vented gasses***

There are two ways for capturing the heat that can be explored. The first is to acquire new heat exchangers for each of the gas outlets, which can then transfer the heat to water for one of the existing purposes. The second way is to divert the hot gas to some other purpose, such as drying, or to one of the existing heat exchangers, eliminating the cost of new equipment.

The most common type of heat exchanger used for this function is a shell and tube type heat exchanger. Shell and tube heat exchangers consist of a large amount of tubes packed together inside a shell (Cengel, 2003). The existing heat exchangers used a cross flow setup, designed for dust filled gas. There are many other heat exchangers, but due to the current equipment suppliers, availability and requirements, only the existing type found on site were considered.

The size of the heat exchanger will differ, depending on the purpose. For electrical generation, the estimated heat lost, based on atmospheric conditions, will not be sufficient. Different methods exist for analysing heat exchangers, each dependent on the available data. With the lack of measuring instruments and data, many assumptions had to be made (Cengel, 2003):

- Heat exchangers are steady flow devices;
- All fluid and gas streams experience very little change in velocity and elevation, thereby assuming negligible kinetic or potential energy changes;

- The outer surface of the heat exchangers was assumed to be perfectly insulated, allowing for no heat exchange to the environment.

The two methods considered were the “log-mean temperature difference method” (LMTD) and the “effectiveness number of transfer units” (effectiveness-NTU) method. The LMTD requires all the temperatures of the gas and liquids into and out of the heat exchangers, this was not available. Only the inlet conditions could be obtained, resorting to the use of the effectiveness-NTU method instead. (Cengel, 2003)

The effectiveness-NTU method was developed by Kays and London in 1955. It is based on a dimensionless parameter called the heat transfer effectiveness ( $\epsilon$ ), which is defined as the actual heat transfer rate ( $\dot{Q}$ ) divided by the maximum possible heat transfer rate ( $\dot{Q}_{max}$ ). (Cengel, 2003)

$$\epsilon = \dot{Q}/\dot{Q}_{max} \quad (28)$$

In order to simplify the calculations, two convenient parameters were defined. The heat capacity ( $C$ ) has been defined as the mass flow ( $\dot{m}$ ) times the specific heat ( $C_p$ ) for the fluid or gas. The capacity ratio ( $c$ ) has been defined as the minimum heat capacity ( $C_{min}$ ) over the maximum heat capacity ( $C_{max}$ ).

$$C = \dot{m} \cdot C_p \quad (29)$$

$$c = C_{min}/C_{max} \quad (30)$$

The maximum heat transfer rate will occur at the fluid with the smallest heat capacity. It is also limited to the difference of the inlet temperature of the water ( $T_{water,in}$ ) and the gas ( $T_{gas,in}$ ). The maximum possible heat transfer rate is therefore defined as: (Cengel, 2003)

$$\dot{Q}_{max} = C_{min} \cdot (T_{gas,in} - T_{water,in}) \quad (31)$$

The number of transfer units (NTU) are defined as the overall heat transfer coefficient ( $U$ ) times the surface area ( $A_s$ ) divided by the minimum heat capacity.

$$NTU = U \cdot A_s / C_{min} \quad (32)$$

The effectiveness of a heat exchanger is a function of the NTU and the capacity ratio. It can be calculated using the formula for a cross-flow heat exchanger with the one fluid mixed and one unmixed. The mixed fluid will be water and the unmixed fluid will be gas. It can be calculated mathematically based on more than 4 tubes: (Navarro & Cabezas-Gómez, 2007)

$$\epsilon = \frac{1}{c} \cdot (1 - \exp\{1 - c[1 - \exp(-NTU)]\}) \quad (33)$$

In the case of a boiler, the above calculation cannot be used and have to be simplified to:

$$\epsilon = 1 - \exp(-NTU) \quad (34)$$

The district heating heat exchanger was found to be a counter flow heat exchanger, which changes the effectiveness calculation to the following:

$$\epsilon = \frac{1 - \exp[-NTU \cdot (1 - c)]}{1 - c \cdot \exp[-NTU \cdot (1 - c)]} \quad (35)$$

With the maximum possible heat and effectiveness calculated, it is possible to derive the actual heat transfer which can be expected from Equation . These calculations were applied to each gas source and each connection type to those sources.

### **3.4.4.3 Sizing of heat exchangers**

The size of the heat exchangers was dependent on the possible uses they may have. The sizes were selected based on the maximum heat transfer rate, calculated using the Effectiveness-NTU method, which also influenced the availability of the heat exchangers.

The inlet water temperatures from the condenser will be about 107 °C, changing the possible energy gains. In the case of district heating, the return temperature of the water is normally in the range of 62 °C and 70 °C in Winter time. The heat transfer will be calculated as above, using the new reference temperature of 62 °C for maximum demand. The annual heat supplied will be dependent on the demand, any heat produced above that will not be of any financial benefit. In order to allow for the sizing of the heat exchanger, the annual production will be calculated the same as above.

The gas temperature measurements ( $T_{gas}$ ) used in the previous chapter for the clinker cooler gas will not be sufficient. The location of the measurements assumed the energy from the gas exiting the cooler can be used. In reality the dust content is much too high. The filter following the clinker cooler will therefore be required to reduce the dust content., which causes the use of the sensor in the venting tower (TK702) instead.

The preheater cyclone gas will use the previously calculated values, due to its dependence on the outlet gas temperature requirements and not the water temperature of the heat systems.

The sizing of the heat exchanger will be based on the maximum achievable value. The results of the connections and the contributions will be based on the effectiveness-NTU method. The average heat transfer rate has been estimated as the average rate during operation only (no zero values included in average). This provides for the size requirement during normal operations.

### **3.4.5 Connection requirements and types**

The identified heat sources have the possibility to be connected to the existing electricity generating and heating systems. The connection possibilities considered were for the preheating and boiling of water for steam generation using new heat exchangers at kiln 7, direct heating of district heating water and increasing the heat at an existing heat exchanger at kiln 8.

In a heat exchanger, the fluid with a small heat capacity rate (caused by a low mass flow) will experience a small temperature change, and vice versa (Cengel, 2003). The increased steam mass flow will benefit the system through increased power output. Some problems will occur, such as increased mass flow through the superheater, which would reduce the outlet temperatures of the superheater. Due to a lack of measured data in this region, it was not possible to calculate this effect, the effect has therefore not been considered.

The steam to electricity conversion efficiency ( $\eta$ ) of the steam turbine is assumed to be 22 %, as per Cementa AB's recommendation for that specific turbine. There are no losses assumed within the system, as well as no conversion losses of heat to steam. The pressures (P) throughout the calculations are also assumed to be constant.

### **3.4.5.1 Steam generation using kiln 7**

One of the methods for connecting to the existing system, is to connect heat exchangers at kiln 7 with the steam drums at kiln number 8. Water from the steam drum at HE-1 and HE-2 can then be diverted to this source for additional steam generation. The steam could be pumped back to the steam drum, which would allow for higher mass flow going through the super heater to the turbine. This setup would allow for steam generation directly from kiln 7 which contributes to the existing mass flow of steam used for electrical generation by the steam turbine.

The connection will allow the electrical system to continue operating normally if kiln 7 is not operational. The disadvantage of the system is that the power generated will be zero for any time that kiln number 8 is not operational, irrespective of kiln number 7's contribution. It is also important to note that kiln 7 will not contribute if the gas temperature is less than the steam drum water temperature.

Steam generation of this kind is only possible if the gas temperature ( $T_{gas}$ ) at kiln number 7 is higher than the temperature of the water ( $T_{water}$ ) in the steam drum. The contribution to the system will be through increased steam generation ( $\dot{m}$ ) and can be estimated through conducting an energy balance across the new heat source at kiln number 7. The heat supplied ( $Q_{HE}$ ) will be dependent on the source. The steam pressure (P) has been taken as the average value of measurements recorded by the operator. The same method can be applied to both HE-1 and HE-2.

$$\dot{m} \cdot h_{sat,wat} + Q_{HE} = \dot{m} \cdot h_{sat,steam}; \quad (36)$$

*if  $T_{gas} > T_{water}$  and P is constant; with h at saturated conditions for P*

The mass flows were calculated by rewriting the energy balance across the heat exchanger:

$$\dot{m} = \frac{Q_{HE}}{(h_{sat,steam} - h_{sat,water})} \quad (37)$$

In the case of HE-1, the setup has a combined boiler and superheater. The increased mass flow through the turbine will cause the mass flow to increase through heat exchanger 2, connected directly to the

system. Fortunately, a bypass exists past the heat exchanger 2, allowing the same mass flow as normally required. It was assumed that this bypass could be used in the way intended, allowing for any new steam generated to affect the super heater and turbine only. The calculations will be based on a pressure of 2,8 MPa, as obtained from the available data.

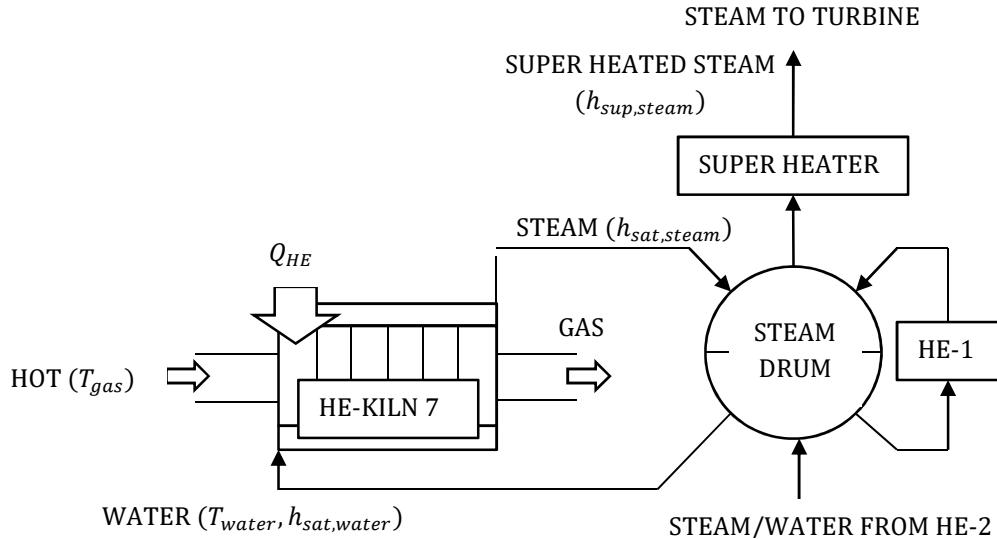


Figure 20 : Layout of new kiln heat exchanger connected to HE-1 steam drum.

In the case of HE-2, the water is heated and boiled using the integrated economizer and boiler. The steam generated will directly increase the mass flow of steam running to HE-1 and consequently to the superheater and the turbine. It will be calculated in the same way, using a pressure of 3 MPa, as obtained from the available data.

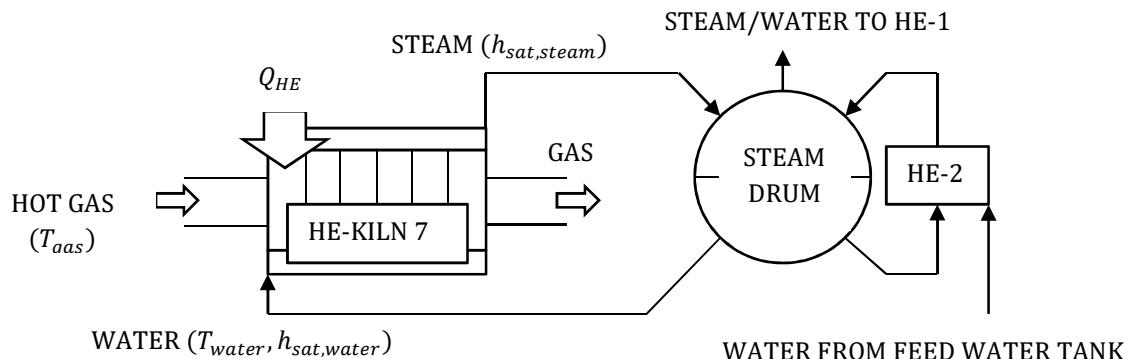


Figure 21 : Layout of new kiln 7 heat exchanger connected to HE-2 steam drum.

The data available were based on the entire heat exchanger, with no data for the various parts, such as the super heater on its own, it was not sufficient for calculating the effect of the changing mass flow.

The GEAB data indicated a constant temperature output irrespective of the conditions around the superheater, as required by the steam turbine. The increased mass flow will increase the heat transfer rate of the superheater, due to the higher temperature difference between the gas and the steam. Under normal circumstances, it will also reduce the output temperatures. The effect could not be analysed due to insufficient data. It has been assumed that the capacity of heat exchanger 1 has not been met and as a result the temperature of the steam after leaving the superheater are assumed to be constant, irrespective of the increasing mass flow.

Assuming all the mass flow is in the form of steam, with no losses, the mass flow is assumed to directly contribute to the electricity generation. This allowed the estimation of the increase in percentage added by the new heat exchanger and the effective increase in the electrical power production ( $El$ ). The amount of electricity added, calculated for each source and at the two steam drums, are shown in Table 11 and Table 12. The sizes of the heat exchangers were estimated as per Chapter 3.4.4.3, with the availability referring to the yearly percentage of hours that electricity could be produced.

$$El = Q \cdot \eta \quad (38)$$

**Table 11 : Energy from connecting kiln 7 to HE-1 steam drum.**

Source	Heat exchanger size (MW)	Availability (%)	Electricity added (kW)	Annual elec. added (MWh/year)
Clinker cooler gas	0,85	36,63	68,9	603,26
Kiln shell – 20m	0,98	71,54	138,0	865,09
Kiln shell - full	5,11	71,54	426,8	2 674,82
Pre-heater cyclone gas	4,42	60,51	648,1	5 677,03

**Table 12 : Energy from connecting kiln 7 to HE-2 steam drum.**

Source	Heat exchanger size (MW)	Availability (%)	Electricity added (kW)	Annual elec. added (MWh/year)
Clinker cooler gas	0,83	31,46	60,29	528,11
Kiln shell – 20m	0,98	71,54	100,22	877,92
Kiln shell - Full	5,11	71,54	309,87	2 714,50
Pre-heater cyclone gas	4,40	58,56	646,05	5 659,40

### **3.4.5.2 Preheating of feedwater**

By preheating the water, a similar outcome can be expected as per steam generation at HE-2, although at higher contribution rates. Preheating the water before HE-2 will increase the temperature, allowing for higher amount of steam to be generated at HE-2 or HE-1. The same effect would be to connect the heat exchanger directly to the saturated water for HE-2, with the only difference being the amount of piping required. The effect on the mass flow from adding additional heat to the system can be calculated using

equation the same method as for steam generation, for the given average pressure of 3 MPa and an inlet temperature of 107 °C:

The minimum temperature requirement for contributing will be much less for water heating than for steam generation. Consequently, more energy contribution will occur. This setup will work for gas temperatures higher than the feed water temperature.

$$\dot{m} \cdot h_{FW} + Q_{HE} = \dot{m} \cdot h_{sat,water}; \quad (39)$$

*if  $T_{gas} > T_{FW}$  and  $P$  is constant;*

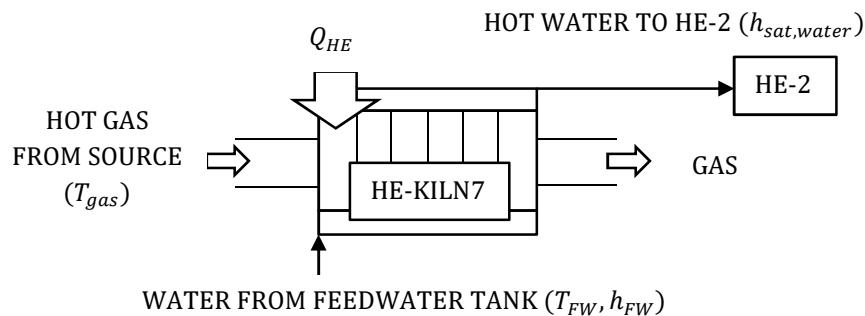


Figure 22 : Layout of kiln 7 heat exchanger connected to feedwater line.

Calculating the mass flow using average values for the temperatures and pressures for each source allowed us to calculate the energy added to the steam turbine.

Table 13 : Energy from connecting kiln 7 to Feed water line.

Source	Heat exchanger size (MW)	Availability (%)	Electricity added (MW)	Annual elec. supply (MWh/year)
Clinker cooler gas	3,53	70,85	0,322	2 002,04
Kiln shell – 20m	0,98	71,54	0,140	877,92
Kiln shell – Full	5,11	71,54	0,433	2 714,50
Pre-heater cyclone gas	4,45	70,56	0,349	2 315,97

### 3.4.5.3 Heating of District Heating water

The aim of such a connection would be to eliminate the dependence on oil for supplying district heat and to allow for more heat going to HE-2 for electricity generation. The connection at kiln 7 can run in series or parallel to the connection at kiln 8. The best approach would be to dedicate kiln 7 to supplying district heat, and use kiln 8 as backup.

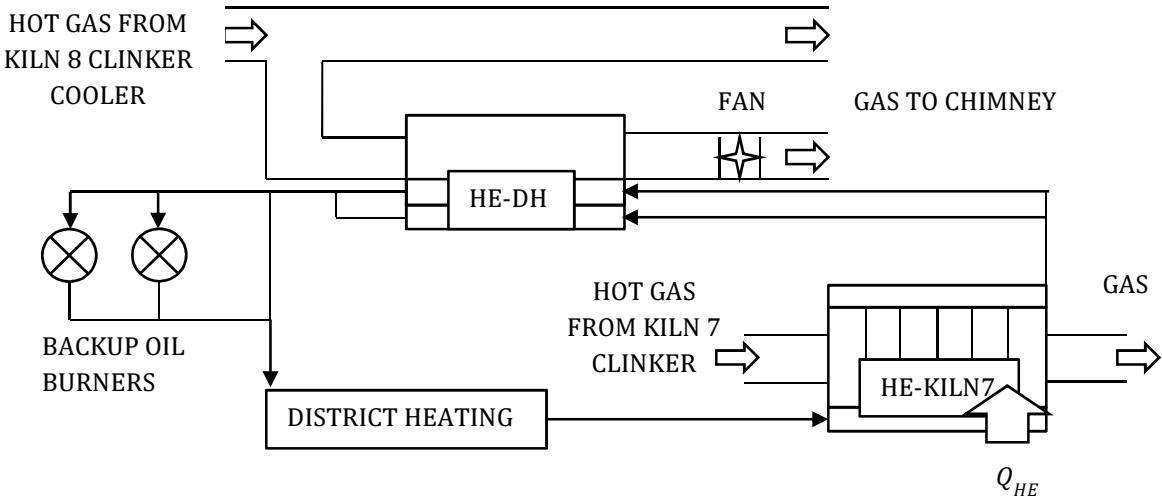


Figure 23. : Layout of kiln 7 heat exchanger connected to district heating system

The demand for oil has changed significantly over the years, with constant reduction from 800 m<sup>3</sup> in 2007 to 400 m<sup>3</sup> in 2011. GEAB confirmed plans to reduce the use of oil even more through operational control. In order to prevent any unnecessary cost due to oversizing of the heat exchanger, the heat requirement for district heating first needed to be investigated. Data from the period 2007 until 2010 has been made available by GEAB, which indicates the heat in MWh for each month, from both the heat exchanger and the oil burners. This allows the creation of the yearly trend, seen in Figure 24, providing a useable yearly demand profile using the average values for each month.

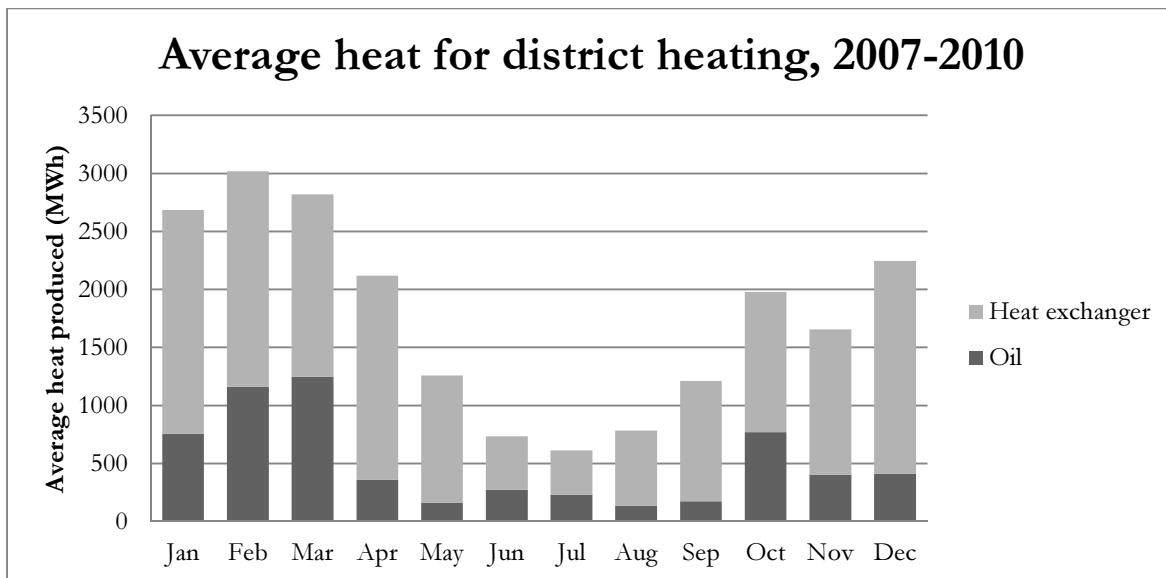


Figure 24 : Annual district heating production profile.

As expected, the highest demand for heat would be in winter time, with very little heat demand in summer. The oil burning is dependent on the shutdown periods, so will vary from year to year. The oil is owned and operated by GEAB. Replacing it would increase the heat supplied and reduce the large costs associated with oil, which would provide for some benefit. The maximum replaceable heat will be limited by the demand.

During maximum demand, the required heat supply needs to be met. By extrapolating the total for 2011 over the average trend, the monthly demand can be estimated. The average heat transfer rate required ( $\dot{Q}_{req}$ ) for each period was calculated as the amount for a given month ( $Q_{month}$ ), divided by the days of the month ( $d$ ) and the 24 hours in a day.

$$\dot{Q}_{req} = Q_{month}/(d \cdot 24h) \quad (40)$$

The amount of heat that can be supplied by connecting kiln number 7 with kiln number 8 district heating was estimated using 20 minute intervals (summed together for each hour) for the one year period covered by the study. Kiln 7's maximum supply is limited by the total demand and transfer rate for 2011. The temperature requirement is much lower, allowing for higher heat transfer possibility.

The calculated heat supplied by each source ( $\dot{Q}_{source}$ ) minus the required transfer rate for each month at the same time step, will give positive and negative values. The positive values represents sufficient supply, the negative represents insufficient supply by kiln 7. For each positive value, the heat used for district heating ( $\dot{Q}_{DH}$ ) is taken as the required rate, for each negative value, the heat used is taken as the supply rate. The total heat covered by kiln 7 ( $Q_{k7}$ ) was calculated based on the sum of the heat for each time instance for the whole year.

$$\begin{aligned} & \text{for } (\dot{Q}_{source} - \dot{Q}_{req}) \geq 0, \dot{Q}_{DH} = \dot{Q}_{req}; \\ & \text{for } (\dot{Q}_{source} - \dot{Q}_{req}) < 0, \dot{Q}_{DH} = \dot{Q}_{source}; \end{aligned} \quad (41)$$

$$Q_{k7} = \sum_{i=1}^{8784} (\dot{Q}_{DH})_i \quad (42)$$

Most of the heat supplied by kiln 7 will take the load off kiln 8, allowing it to produce more electricity. In order to estimate the amount of electricity saved ( $El$ ) by this connection, the above contribution is multiplied by the availability of kiln 8 ( $\% \tau_{k8}$ ) and also the heat to electricity transfer rate, estimated at 9,14 % from data figures available from the plant control room.

$$El = Q_{k7} \cdot \% \tau_{k8} \cdot 9,14 \% \quad (43)$$

The heat supplied by kiln 7 alone is not enough to reduce the oil consumption. Kiln 8 is therefore still part of the system, but as secondary backup. When kiln 7 is unable to supply, kiln 8 will step in. According to the control centre staff at GEAB, burning of oil is avoided for as long as the gas temperature at kiln 8 is above 180 °C. The amount of heat supplied, by either kiln 7 or kiln 8, to the district heating system is

estimated for each time step. For any time step that the heat used is lower than the required heat, kiln 8 will add its contribution. The entire heat requirement was assumed to be satisfied whenever kiln 8's clinker cooler gas temperature ( $T_{gas}$ ) is above 180 °C, setting the heat used for district heating to the required heat. The sum of the heat used for district heating will provide the total heat covered by both kilns ( $Q_{k7\&8}$ ) for district heating. Following through on equation:

$$for \dot{Q}_{DH} < \dot{Q}_{req} \text{ and } T_{gas} \geq 180^\circ\text{C}, \dot{Q}_{DH} = \dot{Q}_{req} \quad (44)$$

$$Q_{k7\&8} = \sum_{i=1}^{8784} (\dot{Q}_{DH})_i \quad (45)$$

The amount of heat still supplied by oil ( $Q_{oil}$ ) will therefore be the difference between the heat demand for 2011 ( $Q_{demand}$ ) and the heat supplied by both kilns. The volume of oil burned ( $V_{oil}$ ) was estimated from the heat supplied by the oil times the heat contained in the oil, 8,736 MWh/m<sup>3</sup>.

$$Q_{oil} = Q_{demand} - Q_{k7\&8} \quad (46)$$

$$V_{oil} = \frac{Q_{oil}}{8,736} \quad (47)$$

The financial savings from oil ( $S_{oil}$ ) can therefore be calculated as the volume of oil burned, times the cost of oil (±7000 SEK/m<sup>3</sup>) and the percentage of ownership (50 %).

$$S_{oil} = V_{oil} \cdot Cost \cdot 50 \% \quad (48)$$

The savings from increased electrical production at kiln 8 ( $S_{elec}$ ) will therefore be the amount of electricity increased times the cost of electricity (±520 SEK/MWh).

$$S_{elec} = El \cdot 520 \text{ SEK/MWh} \quad (49)$$

The total saving will be the sum of the electrical and oil savings. Although the values below seem rewarding, it is important to remember that the savings are dependent on the demand, which has been reducing. The oil consumption could also be reduced through using different operational and distribution strategies.

**Table 14 : Energy and returns from connecting to the district heating system.**

Source	Heat exchanger size (MW)	$S_{oil}$ (k.SEK/year)	$S_{elec}$ (k.SEK/year)	$S_{total}$ (k.SEK/year)	Heat recovery (MWh/year)
CC gas	4,73	1 059	312	1 372	17 289,18
Kiln shell – 20m	0,98	524	81	605	9 951,47
Kiln shell - Full	5,11	1 620	253	1 873	17 392,27
PHC gas	4,53	804	237	1 041	17 806,00

### **3.4.5.4 Gas diversion to heat exchangers**

Heated gas, which would normally be vented to atmosphere, has the potential to be diverted to one of the existing heat exchangers. The diversion of the gas, avoids the installation of a new heat exchanger through using the existing one at kiln 8. Such a connection does have potential, but many limitations also exist, such as property differences, process requirements and operation restrictions.

Preheater gas are used largely by the raw mill, therefore diverting it would directly influence the process. Connecting to kiln 8's HE-1 will also not be considered, due to the possible negative effects on kiln 8's rawmill. The only connection possibility would be to connect the clinker cooler gas from kiln 7 to either HE-2 or the district heating heat exchanger from kiln 8.

The best setup will have the gasses separated and controlled independently. Mixing the gasses has the problem of pressure and temperature differences. The gas from kiln 7 has a lower temperature, which would reduce the heat of the mixture. The pressure difference could create problems upstream, due to the changes in gas flows caused by this pressure difference. The connection could also prove difficult due to the fluctuating heat demand and the control thereof through partially open vents.

Contribution by kiln 7 will only be made when HE-2 is being bypassed, or when district heating demand is sufficiently low. Sensors connected to the vents provide data for when HE-2 is completely bypassed.

It is possible to estimate the benefit to the electrical system during complete bypass of HE-2 and the use of kiln 7 gas for supplying heat directly. The maximum heat supplied ( $Q_{achieved}$ ) by kiln 7 was calculated from the average volume flow ( $\dot{V}$ ) of the gas. The specific heat and temperatures ( $T_{gas,in}$ ) of the gas were obtained from hourly values for the entire year, with the steam temperature ( $T_{sat,steam}$ ) taken as the average required by the boiler. The electricity supply was calculated using the previous sections equations, with the requirement that the vent opening for kiln 8 is less than 10 % open.

$$Q_{achieved} = \dot{V} \cdot \sum_{k=1}^{8760} C_{p,k} \cdot (T_{gas,in} - T_{sat,steam})_k \quad (50)$$

*if  $\tau_{vent} < 10\%$  and  $Q_{achieved} > 0$*

It is important to note that no benefit will be achieved during a complete shutdown of kiln 8. It is required that the outlet temperature of the gas will be no less than the desired output temperature of the steam, therefore if the steam temperature exceeds the gas temperature, no heat transfer will take place.

**Table 15 : Energy from connecting kiln 7 to HE-2 using only gas and separated systems.**

Source	Usability	Power added	Annual electricity supply
Clinker cooler gas	22,75 %	10,12 kW	88,63 MWh/year

Another potentially beneficial connection would be to connect the gas to the district heating heat exchanger directly. The aim is not to deliver as much heat as possible, but instead to deliver enough heat to avoid the burning of oil. The heated gas from kiln 7 clinker could be used as soon as kiln number 8 is taken off line, or to prevent the bypassing of HE-2 during low heat requirements.

The district heating heat exchanger is a cross flow heat exchanger consisting of two sections, for which both will be modelled as one section. It was possible to initially analyse the heat exchanger using the LMTD method. This was done in order to determine the overall heat transfer coefficient ( $U$ ) and the surface area ( $A_s$ ).

The temperature and heat transfer readings for a specific point during operation were made available. The first step was to calculate the value of  $U \cdot A_s$  using the calculated mean temperature difference ( $\Delta T_m$ ) and heat transfer rate ( $\dot{Q}$ ).

$$U \cdot A_s = \dot{Q} / \Delta T_m \quad (51)$$

The  $U \cdot A_s$ -value were found to be 80,5 kW/°C.

A change in inlet temperatures will result in new outlet temperatures. This eliminated the possibility of analyzing the heat exchanger for new kiln 7 gas inlet conditions using the LMTD-method. Assuming a constant  $U \cdot A_s$ -value, it was possible to evaluate the effects of changing inlet temperatures using the Effectiveness-NTU method. The estimated heat requirement could be compared to the calculated heat transfer rate of the new inlet gas. As per the previous calculations, the values were calculated for each time step, using the  $U \cdot A_s$ -value, allowing for the calculation of the NTU. The results obtained can be seen in Table 16.

By evaluating the gas temperature at specific times, it was possible to determine the amount of oil burning that can be avoided. The oil burning reduction savings ( $S_{oil}$ ) was calculated using the volume of oil burned in 2011 ( $V_{oil,2011}$ ), amounting to 400 m<sup>3</sup>, minus the newly calculated value ( $V_{oil,new}$ ), amounting to 127,57 m<sup>3</sup>, times the cost of oil at 7 000 SEK/m<sup>3</sup> and the 50 % company share.

$$S_{oil} = (V_{oil,2011} - V_{oil,new}) \cdot 7\,000 \frac{\text{SEK}}{\text{m}^3} \cdot 50 \% \quad (52)$$

**Table 16 : Heat from connecting kiln 7 to district heating using only gas**

Source	$S_{total}$	Electricity recovered	District heating
Clinker cooler gas	738 k.SEK/year	2,61 MWh/year	1 653,52 MWh/year

### 3.4.6 Other uses

Many other uses for heat exist, but few of them can be considered sufficiently beneficial to the cement plant or the community. Studying the energy losses within the cement manufacturing process allowed for

the identification of a major loss in the process, wet fuels. Large amount of energy is used for the combustion of wet fuels. The opportunity therefore exists for preheating the fuels, which would reduce the moisture content and improve the efficiency of the burning process.

### **3.4.6.1 Drying of fuels**

Part of many measures to reduce carbon emissions has been related to the use of alternative fuels. Currently, kiln 7 uses coal only, although alternative fuels are being combined and mixed in the burner of kiln number 8.

Alternative fuels can vary between tyres, animal residue, sewage sludge, waste oil and solid fuels recovered from industry and municipalities (Schneider et al., 2011). The use of these fuels can be limited due to equipment, chemical processes, regulations and availability. Kiln number 8's burner currently uses coal, wood pellets and waste which consist of shredded paper, plastics, textiles and rubber. One of the features currently related to the use of alternative fuels is the high moisture content. The increased moisture requires more energy for proper burning, which can be reduced through low temperature drying.

The low temperatures ( $<100^{\circ}\text{C}$ ) from the gas vented after heat removal in the heat exchangers is a perfect source for low temperature drying. Exposing the alternative fuels to the gas will reduce the moisture content, which in turn will improve the burning efficiency of the fuels.

Alternative fuels form a significant part of future strategies and will possibly become an important investment opportunity in the future. For the sake of this study, which focuses more on the existing system, a detailed study will not be done.

### **3.4.7 Preliminary discussion**

The results indicates generally, long term investment opportunities. The intention was to maximize the heat recovered with added importance to cost effectiveness (estimated using payback periods). The results of each connection type are listed in Table 17. Comparing the values of each connection allowed for the selection of the most feasible setup, taking into account that each source can only be used for one separate connection type.

The clinker cooler gas indicates the best heat recovery when used for district heating directly, followed by the use for feed water heating. The difference between the two values is most likely from availability of the system. The most suitable connection for both heat recovery and payback would be the district heating connection.

The fully covered kiln shell has the expected advantage of greater heat recovery than that of the partially covered (20 meter) shell. Only one can be selected for the purpose of heat recovery. The highest heat recovery occurs by connecting the secondary shell to the district heating system, followed closely by the feed water connection and steam generation. The closeness of the values and the conflict arising from one

the clinker cooler connection, leads to the selection based on the payback period. The most suitable use for the secondary kiln shell would be to heat the feed water of the steam turbine system.

The preheater cyclone connection has the highest heat recovery for connecting to the district heating, although at a very high payback period. It also conflicts with using the clinker cooler as the source. Without reducing the heat recovery too much, the connections to the steam drum at HE-1 shows to be the best connection type in this regard.

The results indicate high payback times with low heat recovery relative to its potential. Any smaller sources would not be considered due to the expected poor heat recovery and increased payback periods.

**Table 17 : Summary of the costs, savings and payback period for all possible connections.**

Connection		Capital cost (k.SEK)	Savings (k.SEK/year)	Heat recovery (MWh/year)	Payback period (Years)
Steam at HE-1:	Clinker cooler	4 002	313	2 742,11	12,76
	Kiln shell – 20m	5 630	449	9 607,05	12,52
	Kiln shell – Full	15 146	1 390	29 704,78	10,89
	Pre heater	22 970	2 952	25 804,96	7,78
Steam at HE-2:	Clinker cooler	2 895	274	2 400,51	10,54
	Kiln shell – 20m	5 752	456	9 607,05	12,60
	Kiln shell – Full	15 233	3 398	29 704,78	4,48
	Pre-heater	24 093	2 942	25 724,55	8,19
Feedwater:	Clinker cooler	10 247	1 918	16 773,94	5,34
	Kiln shell – 20m	5 332	456	9 607,05	11,68
	Kiln shell - Full	14 848	3 398	29 704,78	4,37
	Pre-heater	24 085	2 614	22 855,77	9,21
District heating:	Clinker cooler	13 674	2 925	17 241,81	4,67
	Kiln shell – 20m	5 332	835	9 951,47	6,38
	Kiln shell – Full	14 848	1 614	17 392,27	9,19
	Pre-heater	24 493	3 117	17 158,77	7,86
Clinker cooler gas to HE-2		9 669	216	402,87	209,81
Clinker cooler gas to district heating		10 843	738	13 816,39	14,66

## **3.5 Final system and conclusion**

The most feasible connections, established in the previous section, were based on rough estimations. The connections required more detailed and inclusive analyses before recommendations could be made. An additional simple analysis was also requested by the company and can be found in the Appendix.

The new setup of connections allowed for the selection of a possible site layout. The new layout serves as references for improved material estimations and structural requirements. Previously ignored requirements and benefits, such as reduction in greenhouse gas emissions, were also investigated. All the new information allowed for improved financial estimates for each connection.

The additional information and improved results of all three sources and connections, as a whole and as separate installations, proved for the most effective use of excess heat in the Slite cement plant. Final recommendations could be made, based on the results, informing the reader and Cementa AB on the best course of action.

### **3.5.1 Setup**

The most significant restriction was the availability of one source per function. This has led to the selection of connections for the clinker cooler gas, kiln shell and preheater gas. The final solutions were investigated as separate entities and as one system. For lower cost installations, separate installation will be most beneficial, but the possibility exists to benefit from reduced contractor rate and higher returns if the connections are installed under a single contract.

Clinker cooler gas should be utilized through the installation of a 5,41 MW cross flow heat exchanger, designed for dust filled gas. The heat exchanger should be connected to the district heating system directly, before it connects to the heat exchanger at kiln 8. All the heat requirements will be provided by the clinker cooler gas. In case the clinker cooler at kiln 7 cannot deliver enough heat, the existing heat exchanger at kiln 8 should serve as backup or booster. Such a setup will reduce the bypassing of HE-2, which in turn would improve the steam generation for electricity. A large amount of the oil burned for the district heating would also be reduced. The change in operation and setup of the system will have minor effects on the equipment involved.

Additional minor benefits from the clinker cooler gas connection might occur, but these would be counteracted by added requirements and was therefore assumed to be negligible. With less demand placed on the heat exchanger at kiln 8, the requirement on the fan operating with this heat exchanger would be reduced. This reduction would lead to energy savings through reduced electrical needs. This saving would be counteracted by the increased pressure drop which would occur at kiln number 7. The presence of a new heat exchanger would put more demand on the fans used at the clinker cooler to maintain the same volume flow, increasing the electricity consumption. No additional pumps are required, with the control still maintained through using the existing equipment.

The secondary shell, which would completely cover kiln number 7, would be ideal for connecting to the feed water line. The secondary shell has the potential to provide an additional 4,74 MW of heat to the feed water, raising the temperature and reducing the requirement on HE-2. The effect will be an increased amount of steam generation at the existing heat exchangers, adding to the electricity generation.

A secondary effect of such a setup would be the reduced heat loss from the kiln shell. The reduced heat loss would have the effect of reducing the heat requirement from the burner, thereby adding to fuel savings. The added pressure drop that will occur can be remedied through increasing the pressure of the existing feedwater pump.

The preheater cyclone heat exchanger would benefit the electrical generating system though increased steam generation. By diverting water from the steam drum of HE-1 and adding heat, additional steam will be generated. The steam is returned to the steam drum from where it would be sent through the super heater and finally the steam turbine. An increase in the generated electricity will occur.

The connection has some added benefit through the exclusion of the cooling tower. The heat exchanger would have to be controllable to allow for the raw mill operation requirements. The savings will relate to a reduction in water consumption and minor electrical savings from equipment such as pumps. By bypassing the cooling tower, additional heat would also be made available for the manufacturing of white clinker. Such a system would require its own loop, connecting the water to the heat exchanger and then sending the steam back to the steam drum. An additional pump will therefore be required in order to maintain this loop.

Connecting all three of the connections is also a possibility which would maximize the heat recovery. A foreseeable negative effect is from the connection of the secondary kiln shell and the fuel reduction this may cause. By reducing the amount of fuel burned and consequently the air requirement, the gas flow exiting the preheater cyclones and possibly the temperature could be reduced. The consequence would be a reduced amount of steam production from the heat exchanger and reduced electricity generation. A diagram indicating the new connections and how it integrates, derived from Figure 13, can be seen in Figure 25.

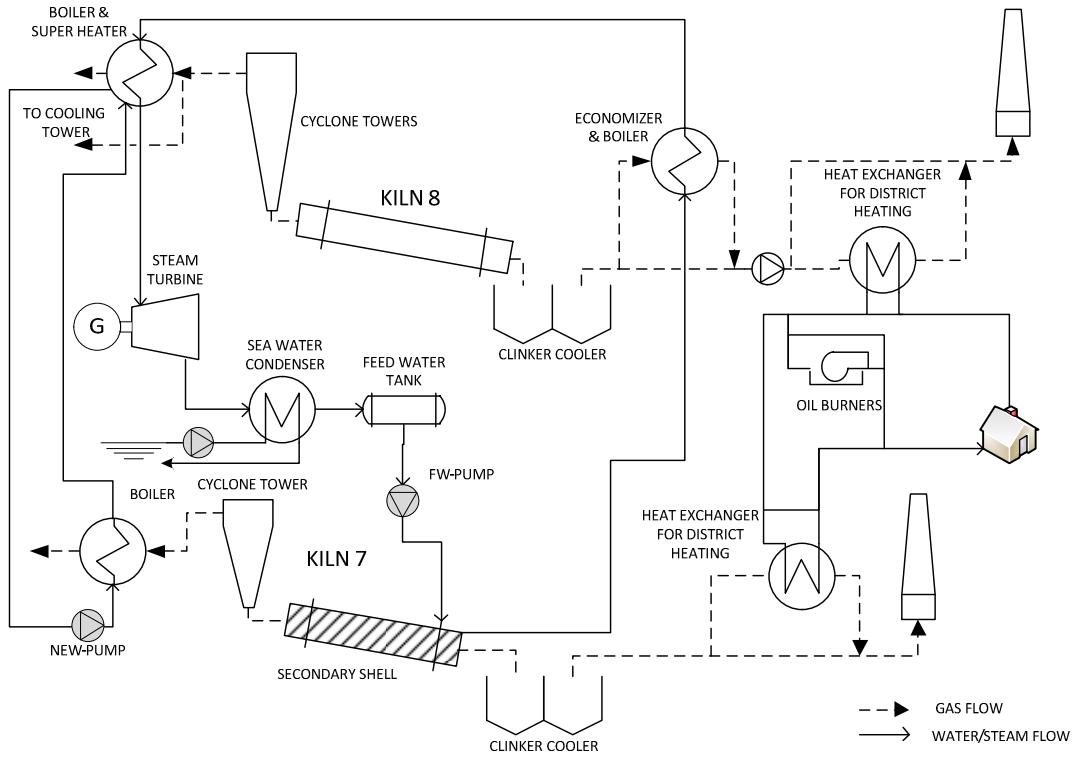


Figure 25 : Simple diagram of new system layout and connections.

### 3.5.2 Layout

An overall layout of the new system, indicating the location of the new heat exchangers and piping in a scaled figure, will provide for a better understanding of the impacts and requirements. Understanding the location will also provide insight into possible positive and negative infrastructural issues that might exist. The general layout can be seen in Figure 26 with the estimated positions of the new equipment.

The new clinker cooler heat exchanger has the advantage of being located next to one of the main district heating pipes, as can be seen in the north-eastern section of kiln 6 in Figure 26. Additional cost saving can therefore be achieved through connecting the heat exchanger directly to the district heating line. The hot water pipes run underground mostly, but appears above ground before running towards the East, where it would be ideal for a new connection.

The new pre heater cyclone gas heat exchanger has been found to be more problematic, as seen in the north-western part of kiln 7, next to the preheater cyclone tower. The best location to install it is currently occupied by redundant equipment, which would have to be removed. There is an additional requirement for constructing a new pipe bridge, in order to connect to HE-1. There are also some elevation differences. The top of equipment elevation for HE-1 is 49 meters which will have to be connected to the new heat exchanger, estimated at 70 meters elevation.

The kiln shell can potentially be connected from one side only. It has the benefit of having a low elevation, almost equal to the steam pipes', and relatively close proximity to the steam pipes. The connection could be made as the piping runs across kiln 7's tower, before it lifts over the road and enters HE-2.

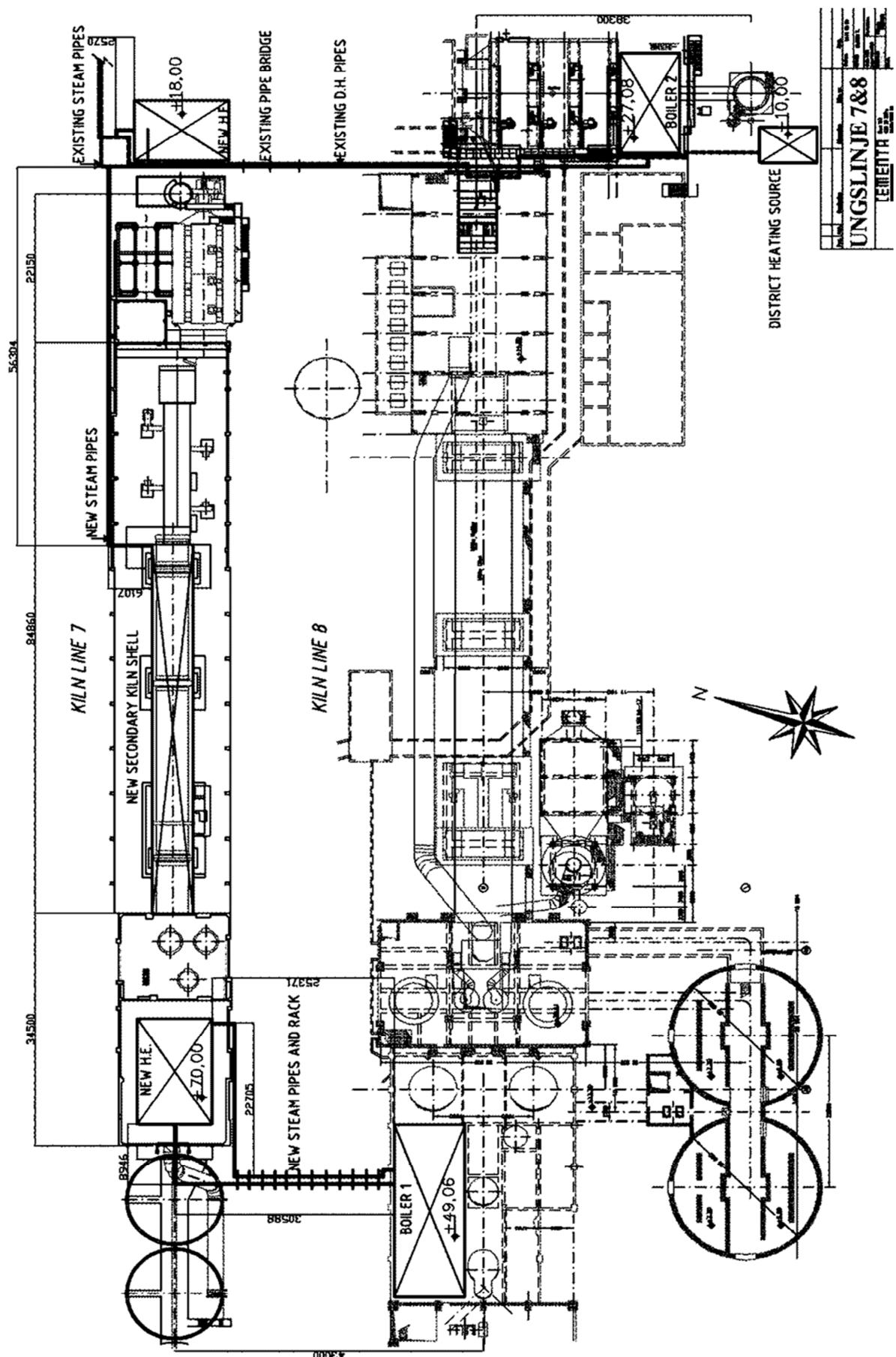


Figure 26 : Top view of kiln 7 and 8, with new heat exchangers and piping.

### **3.5.3 Heat recovery**

The energy recovery calculated for the sources are considered to be sufficient. The heat recovered, refers to the heat which is recovered from the source and excludes any secondary contributions. The uses may vary in size and function. The net energy from gains and losses through removal of existing or adding of new equipment are assumed to be negligible. Energy savings are expected to remain as per calculated values.

Connecting the district heating to the clinker cooler gas will allow for the recovery of 17,24 GWh of heat per year or 34 % of the available heat. The heat recovered will mostly benefit the district heating system, replacing the heat exchanger at kiln 8. The clinker cooler gas from kiln 7 will be able to supply 87 % of the district heating requirements, with the remainder supplied by kiln 8 and the oil burners. The bypassing of kiln 8's district heating heat exchanger will increase the amount of electricity generated at the steam turbine by 3,79 GWh per year, or a total increase of 15 % of the electricity generated.

The preheater gas connected to HE-1 will provide 25,80 GWh of heat per year. This amount of heat indicates a recovery of 71 % of the available heat. The heat will produce steam which will increase the electricity generated by 5,68 GWh per year, or 23 % of the total electricity generated.

The secondary shell heat exchanger will reduce heat losses, but also remove heat from the shell. The radiation heat losses to the environment would be replaced largely by radiation heat losses to the secondary shell tubes, although at a lesser extent (due to higher inlet temperatures). The amount of heat recovered from the shell will amount to 29,70 GWh per year, or 57 % of the total kiln losses. The heat recovery provides for increased electricity generation of up to 6,54 GWh per year, or a total of 27 %, through the preheating of feedwater, while the reduction in heat losses will translate to fuel savings. Assuming that all the convection losses are translated to fuel savings, it would result in 19,75 GWh per year reduction in heat requirement from fuel.

The total amount of heat recovered will amount to 72,75 GWh per year, which amounts to 52 % of the heat lost through the three sources. The additional electricity generated through all the connections are estimated at 16 GWh per year, or 65 % of the total electricity generated.

### **3.5.4 Environment**

The environmental improvement of the setup only focuses on the current concerns of Sweden, the amount of CO<sub>2</sub> emissions, water savings are not yet of concern and were not considered. Due to the complexity of determining the source of electricity, with Sweden using a large amount of nuclear and hydro power, only the direct emission reductions at the plant were considered.

The reduction in oil burned for district heating, due to the clinker cooler connection, will save a significant amount of CO<sub>2</sub> emissions. Due to the mixture of oils, the average emissions factor ( $Eo_{av}$ ) of the two fuels

(Eo1 as 74,3 and Eo7 as 77,4) had to be used. The emission reduction was calculated using an estimated heating value ( $h_{oil}$ ) of 40 MJ/kg and a density ( $\rho_{oil}$ ) of 0,9 kg/m<sup>3</sup>. The estimated volume savings ( $V_{oil}$ ) are 272,42 m<sup>3</sup> of mixed diesel grade oil per year.

$$kg.CO_2 = Eo_{av} \cdot \rho_{oil} \cdot V_{oil} \cdot h_{oil} \quad (53)$$

The reduction in CO<sub>2</sub> emissions are estimated at 348,36 ton per year. This value can be improved further through improved operating conditions.

The other source of CO<sub>2</sub> emissions reduction would be from the reduction in fuel demand. A 19,75 GWh per year reduction in heat lost from the kiln would amount to 2 896 ton of coal per year, which is about 4,8 % of kiln 7's current consumption. With a conversion factor, 2,4 ton CO<sub>2</sub> per ton of coal, for the coal used on site, the amount of CO<sub>2</sub> emission reduction would be 6 950,4 ton.

The reduction in CO<sub>2</sub> emission will improve the company's environmental standing, allowing it to benefit from future regulations and maintain a good name within the industry. The possibility also exists for the future participation in carbon trading, which might see large financial benefit go to the cement plant.

### **3.5.5 Finance**

The project cost and payback period were important features within the project. The project had to deliver on possible returns within an acceptable amount of time. The costs were estimated for each installation and adjusted for improved accuracy. The costs, especially the returns and savings, are highly dependent on the installation date, which will be discussed in brief in order to establish a more accurate payback time.

Financing of projects occur through the parent company, Heidelberg Cement Group. Each year, Cementa AB issues Heidelberg with a list of projects, to which Heidelberg approves and provides for the requested budget. The list for 2013 has been completed and consequently, the possibility of including the project related to this report has shifted to 2014. The current estimations for the capital costs will be adjusted by two years, taking into account the projected inflation rate.

The inflation rate was estimated from using the yearly average Consumer Price Index (CPI) of Sweden. The composite inflation rate ( $i$ ) was calculated based on a 16 year historical trend (Kandpal & Garg, 2003), from 1996 until the end of 2011, obtained from Statistics Sweden (Statistics Sweden, 2012). The composite inflation rate was found to be 1,23 % for the given period.

$$i = \left( \frac{CPI_{2011}}{CPI_{1996}} \right)^{1/16} - 1 \quad (54)$$

The capital costs calculated in the previous chapter were based on rough estimations. The final results were adjusted for the new setup. Previous calculations also did not include for additional equipment costs, such as pumps and fans, which were added in this section.

The savings obtained through electricity ( $S_{el}$ ) and oil ( $S_{oil}$ ) reduction were estimated as per previous chapter, adjusted for the projected future costs. The savings ( $S_{2014}$ ) are projected for 2014 for each year ( $n$ ), such as were done for inflation. (Kandpal & Garg, 2003)

$$S_{2014} = S_{oil} \cdot (1 + p)^n + S_{el} \cdot (1 + e)^n \quad (55)$$

Oil and electricity savings (financial) are dependent on the expected growth rate in the price of the two. The growth rate of the electricity price ( $e$ ) and the growth rate of the oil price ( $p$ ), increase the oil savings and electricity savings each year and reduces the payback period. This growth rate was calculated as a geometric series between the period 2008 and 2012, increasing annually by 0,71 % for electricity and -3,03 % for oil. The sum of these values provide for the expected accumulated saving ( $S_n$ ) after a certain amount of years ( $n$ ). (Kandpal & Garg, 2003)

$$S_n = S_{oil} \cdot \left[ \frac{1 - (1 + p)^n}{-p} \right] + S_{el} \cdot \left[ \frac{1 - (1 + e)^n}{-e} \right] \quad (56)$$

An additional annual loss has been added to account for possible maintenance costs of 1,5 % of equipment and installation costs. This cost will increase at the same rate as inflation for each year, increasing the payback period. (Kandpal & Garg, 2003)

$$C_n = 1,5\% \cdot P_{2014} \cdot (1 + i)^n \quad (57)$$

**Table 18 : Cost estimation for final setup, projected for 2004.**

Items	Clinker cooler		Full Kiln Shell		Preheater Cyclone	
	District heating		Preheating feed water		Steam HE-1	
	Investment Costs					
Items	Quantity	Costs (k.SEK)	Quantity	Costs (k.SEK)	Quantity	Costs (k.SEK)
Pipes	34 m	122	123 m	440	138,15 m	496
Bridge	0 m	0	0 m	0	25,37 m	104
Heat exchanger	1 piece	13 845	1 piece	14 714	1 piece	23 092
Equipment destruct		0		0	1 piece	2 049
Electrical equipment		0		0		102
Total		<u>13 967</u>		<u>15 154</u>		<u>25 844</u>
Earnings						
	(MWh/y)	(k.SEK/y)	(MWh/y)	(k.SEK/y)	(MWh/y)	(k.SEK/y)
Electricity	3 793	2 001	6 535	3 447	5 677	2 994
Oil	2 379	925	n.a	0	n.a	0
Total		<u>2 925</u>		<u>3 447</u>		<u>2 994</u>
Expenses						
Maintenance	1,5%	<u>210</u>	1,5%	<u>227</u>	1,5%	<u>348</u>
Payback						
	(years)		(years)		(years)	
Payback period		5,6		5,0		10,9
Date		01/2020		06/2019		06/2025

The planned budget is usually finalized midyear, allowing for project planning to occur from mid-2013 until the beginning 2014. All tie-ins required for the project can only occur during a planned shutdown, which occurs in Spring. The start of operation for the equipment has been based on the current shutdown and has been assumed for 1 June, 2014.

### 3.5.6 Recommendations

The feasibility of the evaluated connections will be reduced due to planned changes in production, as well as design concerns. These issues make it less attractive for the company to undertake the project. In order to provide the company with a project that is economically valid which fits into future planning, installation of only part of the above project will be recommended.

The preheater connection has proven to be insufficient. The high equipment and installation costs increase the payback period to more than 10 years, which will increase even more with lower availability. The preheater gas can only be used for heat recovery when normal clinker is being manufactured. Low alkali clinker requires the maximum amount of heat from the gas, preventing the removal of heat for

steam generation. The plant has future plans to increase the manufacturing of low alkali clinker, reducing the heat recapturing from this source. It is therefore recommended that the company exclude the installation of the preheater gas connection.

The secondary kiln shell has a large amount of potential, although mostly theoretical. It has not yet been implemented within industry and first needs to be tested before implementation. The design of the secondary shell needs to be improved and perfected to incorporate the requirements, such as monitoring and cooling abilities, for use in this specific cement plant. The plant has the additional potential of connecting to kiln 8's shell, allowing for even more heat recovery and loss reduction. It is therefore recommended that more detail design work first be done on the secondary shell before consideration. Its installation will therefore be moved further by a few years, until the detailed design has been completed.

The plant intends to increase its use of alternative fuels in the next few years, increasing the feasibility of using low heat for drying of alternative fuels. It is recommended that further studies should be done, investigating the feasibility of using low heat for drying of these fuels, especially if sewerage sludge becomes one of the alternative fuels.

Another source of income would be from electricity certificates. More effort should be placed into addressing the current shortcomings caused by the changes in regulation. The benefit previously derived is estimated at 1 million SEK per year from the certificate scheme.

Based on the above recommendation, only the clinker cooler gas connection should be installed at this moment. It will provide for reduced CO<sub>2</sub> emission, an acceptable payback period, increased electricity generation and is relatively low cost compared to the other options. No conflicting events or projects could be foreseen, based on the future outlook of plant, and it would therefore be the most effective use of excess heat at the cement plant.

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## Appendices

### A: Cementa AB heat recovery estimation

The company additionally requested a basic heat recovery analyses focusing on the final recommendation and not based on existing measurements. This analysis assumes exactly 2 weeks downtime in March and full operations throughout the year. The heat recovery of the heat exchanger is assumed to be equal to its size.

With the above assumptions, the clinker cooler connection will provide all the heat for district heating, with exception of the two week period. By assuming the oil consumption from Figure 24, the average energy obtained from oil over the 2 week period is 1 194,23 MWh, with the remainder supplied by the heat exchanger. As per described in Section 3.4.5.3, the savings are shared 50/50 between Cementa AB and GEAB.

The electricity savings at kiln 8, due to the prevention of bypassing HE-1, were estimated as per described in Section 3.4.5.3. It was based on the projected 2011 district heating demand, excluding the 2 weeks downtime assumed for March. These values can be seen in

The cost and payback period were calculated as per Section 3.5.5. Delivering a payback period as per Table 19.

Table 19 : Simple analyses of final recommended solution.

Description	Energy amount	Financial Saving/Cost(-)
Heat exchanger size plus installation costs	5,41 MW	(-)13 967 000,00 SEK
Oil reduction savings	2 300 MWh	921 542,50 SEK/year
Electricity production savings	3 587 MWh	1 865 178,00 SEK/year
Maintenance cost		(-) 210 000,00 SEK/year
Payback Period		5,9 years

## B: Calculations

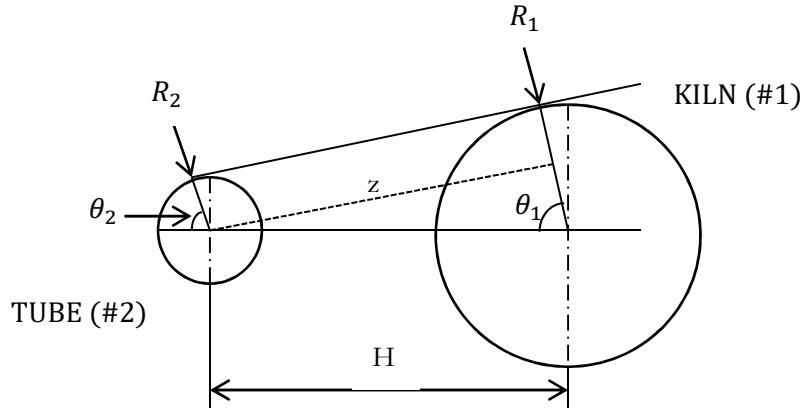
### B-1: Single tube radiation heat transfer

For calculation purposes, the rotary kiln and the cylinder has been assumed as infinitely long parallel surfaces. This allowed for the calculation of the heat gained by first determining the shape factors ( $F$ ) (Cengel, 2003):

$$F_{12} \cdot A_1 = F_{21} \cdot A_2 \quad (\text{B.1})$$

$$F_{21} = \frac{\arcsin\left(\frac{1}{h}\right)}{\pi}; h = \frac{H}{R_1} \text{ and } A \text{ referring to exposed area.} \quad (\text{B.2})$$

The exposed areas of each cylinder ( $A_1, A_2$ ) can be calculated as the circumference of the exposed section, for one meter of length, using the angles of the radial lines ( $\theta_1, \theta_2$ ) connected to the tangent, the distance of the centers ( $H$ ) and the outer radii ( $R_1, R_2$ ) of the cylinders.



$$\theta_1 = \cos^{-1}\left(\frac{R_1 - R_2}{H}\right); \text{with } \theta_2 = \theta_1 \quad (\text{B.3})$$

$$A_1 = 2 \cdot \theta_1 \cdot R_1 \quad (\text{B.4})$$

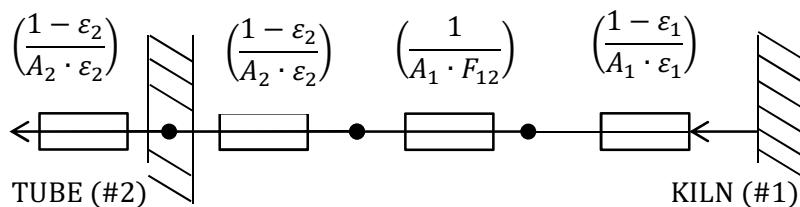
$$A_2 = (2 \cdot \pi - 2 \cdot \theta_2) \cdot R_2; \text{ for each meter of the kiln} \quad (\text{B.5})$$

$$\therefore F_{12} = \frac{A_2}{A_1} \cdot \frac{\arcsin\left(\frac{1}{h}\right)}{\pi} \quad (\text{B.6})$$

Due to the above relation, the shape factor improves with reduced proximity from the shell. The closest workable value of 100mm surface to surface has been assumed and used throughout the calculations. The heat transfer ( $\dot{Q}_{tube}$ ) was calculated using a resistance equation, with the shape factor and the absorptivity of the tube, assumed to be equal to the emissivity ( $\varepsilon_2$ ) which is estimated at 0,79 for oxidized steel.

$$\dot{Q}_{tube} = \frac{A_1 \cdot \sigma \cdot (T_1^4 - T_2^4)}{Z}; \quad (\text{B.7})$$

$$\text{with : } Z = 2 \cdot \left( \frac{1 - \varepsilon_2}{A_2 \cdot \varepsilon_2} \right) + \left( \frac{1 - \varepsilon_1}{A_1 \cdot \varepsilon_1} \right) + \left( \frac{1}{A_1 \cdot F_{12}} \right)$$



As the tube and the water inside heats up, it will also experience radiation and convection losses to the surroundings. The radiation losses were estimated by multiplying the radiation loss of a complete tube with the shape factor of the surroundings, using various temperature intervals for the tube temperature, summed together. A point will be reached where the radiation gains will be equal to the losses to the surroundings. The inlet temperature was assumed to be the same as the atmosphere.

$$\dot{Q}_{tube,rad} = (1 - F_{21}) \cdot \varepsilon_2 \cdot \sigma \cdot A_{tube} \cdot (T_2^4 - T_{atm}^4) \quad (\text{B.8})$$

Losses due to convection also occur, although at a lower level. No accurate wind data on site exists, therefore a fraction of the overall losses (0,53) will be used, as experienced by the kiln shell.

$$\dot{Q}_{tube,conv} = 0,53 \cdot \dot{Q}_{tube,rad} \quad (\text{B.9})$$

An important feature to the technology is the capital cost. The simplicity of the design allowed for an estimation using the cost of the material only. It was assumed that steel pipes of 5mm shell thickness would be used, with the prices per meter length taken from one of the regular suppliers to the plant, Stena Stål.

The heat recovered annually ( $Q_{total}$ ) has been derived from the difference between the absorbed and lost heat for each meter of kiln shell. The sum of the net heat transfer for each meter of kiln shell was then divided by the length of the kiln shell ( $L_{kiln}$ ) to obtain the average yearly heat transfer per meter of pipe ( $Q_{annual}$ ).

$$Q_{total} = \sum_{a=1}^{60} (Q_{tube}(T_{2,a}) - Q_{tube,rad}(T_{2,a}) - Q_{tube,conv}(T_{2,a})) \quad (\text{B.10})$$

$$Q_{annual} = 8760 \frac{\text{hours}}{\text{year}} \cdot Q_{total}/L_{kiln} \quad (\text{B.11})$$

The use of the source will also be dependent on the achievable temperature of the water. Using the calculated heat received by the tube, it is possible to calculate the amount of heat supplied to the water and the maximum obtainable water temperature using a heat balance.

$$\dot{Q}_{tube,abs} = \dot{Q}_{tube,sur} + \dot{Q}_{tube,conv} \quad (\text{B.12})$$

$$\text{rewritten as: } \left( \frac{A_1 \cdot (T_1^4 - T_2^4)}{Z} \right) = 1,53 \cdot (1 - F_{21}) \cdot \varepsilon_2 \cdot A_{tube} \cdot (T_2^4 - T_{atm}^4);$$

$$\text{set: } X = \frac{A_1}{Z}; Y = 1,53 \cdot (1 - F_{21}) \cdot \varepsilon_2 \cdot A_{tube}$$

$$\therefore T_2^4 = \frac{X \cdot T_1^4 + Y \cdot T_{atm}^4}{X + Y} \quad (\text{B.13})$$

The effect of all the related properties has been investigated in order to determine the optimal tube size. The highest amount of energy obtainable for the lowest cost should be the defining factor for selecting the correct size.

**Table 20 : Cost and heat comparison for various sized tubes.**

Tube size (mm)	Cost of Equipment (SEK/m)	Recovered Heat (W/m)	Net heat per Kroner (W/Kr)	Water Temperature (°C)
30	166,80	138,13	558,22	211
50	279,90	251,14	618,72	213
100	595,20	577,63	705,48	219
130	902,30	796,80	655,25	221

## B-2: Concentrated tube

The tube will experience all the radiation received as per calculated in the previous chapter, with additional radiation from the reflection of a parabolic concentrator.

$$\dot{Q}_{total} = \dot{Q}_{tube,abs} + \dot{Q}_{reflected} \quad (\text{B.14})$$

The cost will also increase, with the material cost dependent on the surface area of the reflecting material. The reflector material will consist of highly reflective surface, such as polished aluminium, which can be modelled as covering the area of a parabolic trough with the shape,  $y = \frac{x^2}{4f}$  (Duffie & Beckman, 1991).

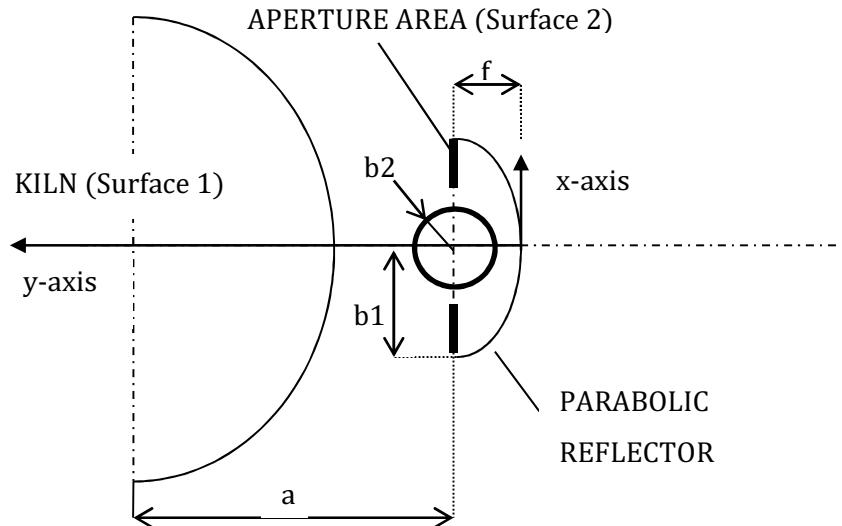
$$A_{refl} = \frac{x \cdot \sqrt{z^2 + x^2} + z^2 \cdot \ln(x + \sqrt{x^2 + z^2})}{z} \quad (\text{B.15})$$

$$\text{with: } z = 2 \cdot f$$

In order to avoid interfering with the thermal cameras located at an angle above the kiln, the concentrator and pipe should ideally fit below and on the opposite side of the kiln shell. The distance between the kiln shell and the structure below it is vast and the size of the reflector should be compared to the amount of radiation captured. Assuming that all the reflected radiation will be concentrated to the tube, the increased amount of heat captured from the kiln can be modelled the same as previously, but with an additional reflection resistance component and a new shape factor. Assuming a highly reflective polished metal is used, the reflectivity can be estimated at 0,9. The new exposure area can be modelled as a flat plate at a distance equal to the distance of the tube.

$$F_{12} = \frac{(\tan^{-1} B1 - \tan^{-1} B2)}{\pi} \quad (\text{B.16})$$

$$\text{with: } B1 = \frac{b1}{a} \text{ and } B2 = \frac{b2}{a}$$



**Figure 27 : Reflector size calculation drawing.**

After testing various sized tubes, it was found that the best achievable result was for the same sized tube as per the results above, 100 mm. The cost ratio is greatly affected by the reflector, reduced cost effectiveness for increasing reflector size. It could be assumed that the reflector protects the tube from the surroundings, with loss reduction of an arbitrarily assumed amount of 80%.

The costs were sourced the same as from the previous chapter and consists of piping and a flat aluminium plate. The heat recovery was calculated using the same approach, with the temperature calculated in a similar manner.

**Table 21 : Cost and heat comparison for various size and distance for thermal concentrated tubes.**

Tube size (mm)	Cost of Equipment (Kr/m)	Recovered Heat (W/m)	f (mm)	Heat per Krone (W/Kr)	Water Temperature (°C)
30	263,37	261,42	300	0,998	254
30	373,82	299,09	500	0,798	242
50	376,47	417,81	300	1,107	258
50	486,91	454,34	500	0,932	251
100	691,77	859,59	300	1,242	255
100	802,22	896,12	500	1,116	252
130	998,97	1 157,53	300	1,159	255
130	1 109,32	1 194,06	500	1,076	250

## C: Equipment and installation costs

The cost estimates used in the report were derived in a linear fashion from the listed costs and sizes below:

**Table 22 : Cost estimate sources.**

Description	Size/QTY	Price	Source
Heat exchanger – Cross flow type for preheater gas	3 MW	6 126 539,05 SEK	Heidelberg Cement Group's estimate for a similar installation conducted in 2008, Turkey.
Installation for preheater gas heat exchanger		9 167 317,65 SEK	
Heat exchanger – Cross flow type for clinker cooler gas	3 MW	4 507 190,52 SEK	Heidelberg Cement Group's estimate for a similar installation conducted in 2008, Turkey.
Installation for clinker cooler gas		4 061 573,53 SEK	
Heat exchanger – Secondary kiln shell structural installation and equipment costs	20 m length	4 786 000,00 SEK	Estimates provided by a Cementa contractor, 2012.
Destruct of existing equipment from kiln 7 cyclone tower structure	Total destruct	2 000 000,00 SEK	Cementa project cost estimate, 2012.
Steam/water pipe equipment and installation	Ø 80 mm	3 500,00 SEK/m	Estimate provided by a Cementa contractor, 2012.
Steam/water pipe bridge structure and installation		4 000,00 SEK/m	
Air duct equipment and installation	56 m	3 399 184,00 SEK	Estimated from the new clean gas duct line at kiln 7 project at Cementa, Slite, 2012.
Appendix item costs:			
Steel pipe	30x5 mm	166,80 SEK/m	Stena Stål price list.
	50x5 mm	279,90 SEK/m	
	100x5 mm	595,20 SEK/m	
	130x5 mm	902,30 SEK/m	
Aluminium sheet	1000x1000 x0,5 mm	90,18 SEK/m <sup>2</sup>	
Steel plate	6040x2500 x8mm	63,97 SEK/m <sup>2</sup>	
Industrial insulation	1000x1000 x50mm	80,96 SEK/m <sup>2</sup>	Alibaba, online industrial shopping website.
Aluminium foil	1000x1000 mm	7,00 SEK/m <sup>2</sup>	Alibaba, industrial shopping website.

## D: Equipment and instrumentation diagrams

The equipment and instrumentation diagrams contain all the information required for the analysis. The instrumentation numbers and locations were identified, as well as the operation, based on these diagrams. The diagrams<sup>2</sup> for kiln 7 appear in the following order:

- Raw mill (“Råkvarn”) and surrounding connections;
- Preheater cyclones layout;
- Rotary kiln (“Ugn”) number 7 and burner;
- Burner layout;
- Clinker cooler (“Klinkerkylare”) layout;
- Filter and chimney, located after the clinker cooler;
- Preheater gas, cooling tower (“Kyltorn”) piping layout.

The diagrams for kiln 8 appear in the following order:

- Clinker cooler gas, filter with heat exchanger 2 for electricity generation (“Avganspanna elgenerering”) and the district heating heat exchanger (“GEAB Spilloärme”) layout;
- Double cyclone towers at kiln 8’s layout;
- Heat exchanger 1 (“Panna 1”) connection to the ducting of the cyclone tower.

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<sup>2</sup> The diagrams are directly sourced from Cementa AB and are therefore all in Swedish. Swedish words are added in brackets to aid in understanding the diagrams.

