The improved heat integration of cement production under limited process conditions: A case study for Croatia

Stanislav Boldyryev[a*], Hrvoje Mikulčić [a], Zoran Mohorović [b], Milan Vujanović [a], Goran. Krajačić [a], Neven Duić [a]

[a]*Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000 Zagreb, Croatia*

[b]*Holcim Croatia d.o.o., Koromačno 7b, 52222 Koromačno, Croatia*

**Corresponding author e-mail: stasboldyryev@gmail.com*

Abstract

Given that cement is the most widely used material for housing and modern infrastructure needs, this paper analyses the energy efficiency of the cement manufacturing processes for a particular cement plant. The cement industry is one of the largest consumers of carbon-containing primary energy sources and one of the primary polluters of the environment, emitting approximately 5% of global pollution. Energy consumption represents the largest part of the production cost for cement factories and has a significant influence on product prices. Given that it is realized in modern society that infrastructural projects lead to a higher level of economy and sustainability for countries, reducing the production cost in the cement industry is a very important problem. The authors analysed the energy consumption of a particular cement factory in Croatia to determine the minimum energy targets of production and proposed pathways to improve energy efficiency. The Process Integration approach was used in this study. Nevertheless, the features of the cement factory forced the research to update its methodological steps to propose real pathways for a retrofit project with the aim of achieving the optimal minimum temperature difference between process streams. There are various streams, including those that contain solid particles, gas and air streams, and streams, that should be cooled down rapidly; these facts become more complicated by the special construction of the process equipment, which causes heat transfer between some streams to be impossible. The main objective of this paper is to determine the potential of real energy savings and propose a solution for a new concept of heat exchanger network (HEN) that avoids the process traps and provides a feasible retrofit. The maximum heat recovery of that production of a particular type of cement was determined and improved when a HEN was built. The authors conclude that the energy consumption of the cement factory can be reduced by 30%, with an estimated recovery period of 3.4 months. The implementation of this retrofit project helps the plant's profitability and improves the environmental impact of the cement manufacturing process.

Keywords: *Sustainable cement production; Cement industry; Energy efficiency; Pinch Analysis*

1. INTRODUCTION

The cement industry sector—as an energy-intensive industrial sector in which energy costs represent approximately 40% of the total production cost and one of the highest CO_2 emitting industrial sectors accounts for approximately 5% of global anthropogenic CO_2 emissions [1]. In 2011, the world cement production, according to the IEA, was 3635 Mt with a predicted increase to 4,556 Mt in 2020, 4,991 Mt in 2030 and 5,549 Mt in 2050 for the high-demand scenario. According to the same scenario, by 2050, the cement producers will be required to reduce CO_2 emissions by 15%, representing a direct reduction of up to 913 $MtCO_2$ [2]. Therefore, the cement industry must adopt more energy-efficient technologies to reduce its environmental impact. However, owing to the large amount of CO_2 coming from the process itself, it will also be necessary to identify the potential for applications of renewables in the cement manufacturing process or even change from conventional production to a new, less CO_2-intensive production process.

Given the significance of the cement industry sector and increased environmental awareness [3], several studies in different parts of the world have demonstrated the energy efficiency of cement plants and CO_2 emission reduction. Much of that work studied the improvement of the cement production process and options for CO_2 emission reduction. Pardo et al. [4] demonstrated the potential for improvement in the energy efficiency of the EU's cement industry and CO_2 emission reduction by 2030. Liu et al. [5] reported the potential for the renovation and building of new cement plants in China. Chen [6] demonstrated the potential technical benefit of the cement clinkering process with compact internal burning of carbon inside a cement shaft kiln. The study showed that the proposed technique can compete with the existing precalciner kiln process. Hasanbeigi et al. [7] demonstrated the abatement CO_2 cost curve for the Thai cement industry. The possibilities and costs of CO_2 abatement were identified considering the costs and CO_2 abatement for different technologies. Worrell et al. [8] presented an in-depth analysis of the US cement industry, showing the possibilities for energy saving and CO_2 emission reduction based on a detailed national technology database. That work emphasized that the most energy-efficient pyro-processing cement manufacturing systems consist of preheaters, a calciner and a rotary kiln. Sheinbaum and Ozawa [9] reported the energy use and CO_2 emissions in the Mexican cement industry, concluding that the focus of the energy and CO_2 emissions reduction should be on the use of alternative fuels. This observation was also confirmed in the study by Mikulčić et al. [10]. Using real plant data and different types and amounts of alternative fuels, the study analysed the environmental impact of cement production. The study showed that the environmental impact of cement production can be reduced if a more energy-efficient process of cement production is utilized along with alternative fuels. Real plant data for the analysis of the parameters affecting the energy consumption of a rotary kiln were used in the study by Atmaca and Yumrutas [11]. The study showed that significant fuel savings can be achieved by minimizing heat losses via effective insulation, reducing the temperature of gases at the outlet, and more effective heat transfer in the unit.

Stefanović et al. [12] evaluated the CO_2 emission reduction potential that can be achieved by partial substitution of cement with fly ash in the concrete. The study further concluded that the quality of the concrete will remain the same. Zervaki et al. [13] studied the physical properties of the cement mortars produced with the use of sludge water. It was proved that sludge water, as well as sludge in a wet or dry form, could be used in the production of mortar without degrading any of its properties. Wang et al. [14] conducted an exergy analysis with use of the organic Rankine cycle and Kalina cycle for cogeneration in a cement plant and found optimal parameters to maximize exergy efficiency. Integration approaches could also be applied to reduce the fuel consumption and emission as reported by Seferlis et al. [15]. These methods are grounded on the thermodynamic approach and have very wide applications in reprocessing industries, as explained by Boldyryev and Varbanov [16]. To utilise waste industrial heat and optimize the site utility system of some energy consumers and producers, Total Site Analysis (TSA) can be used as presented by Klemeš et al. [17]. This methodology was later extended by many researchers. Chew et al. [18] extended the scope of Pinch Analysis for process modifications of individual processes to Total Site Heat Integration and applied the plus–minus principle to enable beneficial process modification options to maximise energy savings. Grip et al. [19] analysed Mathematical Programming using an MILP method, exergy analysis and Pinch Analysis. Experiences and examples of results with the different methods have been given and discussed by different authors. Baniassadi et al. [20] presented applied methodology for the analysis of an industrial energy system based on the modifications of the R-curve concept. This method calculates and most efficient fuel for the utility system. Mian et al. [21] use Pinch Analysis and Process Integration techniques to optimize the energy efficiency of cement production with primary energy consumption of 3,600 MJ/t. They estimated the thermodynamic and exergy-available heat that can be recovered and concluded that heat energy could be reduced by 30%. Nevertheless, the authors did not provide the solution of a retrofit project, nor did they provide the definition of a feasible temperature approach. The previous developments mentioned above were rarely supplemented with proper applications of the methodology, especially for HEN generation. The analysis and application of different methodologies are usually faced with process features of different industrial clusters. In addition, there is a lack of applications of Process Integration approaches in the cement industry owing to its specific process condition and some limitations, including different streams with solid particles, solid–gas and solid–air heat transfer, and streams that should be cooled down rapidly. In appropriate case studies, this approach can be analysed and subsequently used to achieve real savings in the cement industry. Therefore, in this paper, the possibility of and pathways toward maximisation of heat recovery and the concept design of HEN are analysed and developed.

The energy efficiency of a particular cement plant is evaluated such that the total energy consumption of that particular cement plant is compared with the total energy consumption of a benchmark. Currently, the best available technology, the one with the lowest energy consumption, for cement manufacturing is the use of a rotary kiln along with a multistage cyclone preheater system and a calciner. The total energy consumption of such a plant is 2.93 GJ/t, and this value is currently considered as the benchmark [22]. The total energy consumption is also used to evaluate the improvements in the energy efficiency of the cement production process. The current total energy consumption of a kiln process in the Koromač no cement plant, the plant analysed in this study, is 3.65 GJ/t of cement. As seen, there is still space for certain improvement in the energy efficiency of this particular cement plant.

2. PROCESS DESCRIPTION

Quarrying is the first step in the cement production process (see Fig. 1). Inside the quarry that is near the cement plant under study, which is under Holcim's concession for the next 30 years, low- and high-grade marl and limestone are gathered by blasting. After that, the material with granulation of up to 800 mm is transported via dump trucks to the hammer crusher, where it is crushed to the granulation of 0–80 mm for marl and 0–50 mm for limestone.

The high-grade and low-grade marl and quartz (silica corrective material) are then stored separately.

From the storage, the raw materials are transported to the vertical roller mill position No 361 in Fig. 1 (pos. 361), which has a capacity of 170 t/h, and very fine raw meal is produced. The storage of this raw meal consists of 2 silos (pos. 391, 381) with a capacity of 2200 t each.

The fine raw meal from the silos is then fed to the kiln (pos. 461) with a standard capacity of 90 t/h and maximum capacity of 110 t/h. Inside the kiln, approximately 57 t/h of clinker, the main ingredient of cement, is produced. The hot flue gases from the kiln are used to heat the raw mill system, coal mill system, and raw meal in the kiln. The gasses exit the preheating tower with a temperature of 370 ºC. Because the filter bags (pos. 421) cannot withstand temperatures higher than 140 ºC, the flue gasses must be cooled at the cooling tower. The flue gasses at the cooling tower are cooled to a temperature of 175 ºC and to achieve this, approximately 10.5 m^3 of cooling water is used. Afterwards, a fan is used to further reduce the flue gas temperature from 175 ºC to 105 ºC. After the flue gasses are filtered, they go to the stack, from which they are discharged into the atmosphere.

On the kiln outlet side, where the clinker is exiting, the temperature of the clinker is approximately 1450 ºC. At this stage, to preserve the clinker mineral structure i.e., its quality the clinker must be cooled very rapidly to a temperature of approximately 150 ºC. To achieve that, large volumes of air are introduced through 7 clinker cooler fans. This air is then heated to approximately 290 ºC; a smaller part is then used as secondary air to the kiln, and a larger part is applied to heat the cement mill system when it is running. When the cement mill is not running, all of this heat must be removed before the gas reaches the clinker cooler filter bags (pos. 471). The temperature must be lowered to 105 ºC before entering the clinker cooler filter bags, after which the gasses go to the stack. For this purpose, 4 rows of 4 large blowers are used. If the cement mill is running, then less hot air has to be cooled, which translates to less power consumed by the blowers.

The cement grinding process also requires hot gases. They can be extracted from the clinker cooler or, in the case when the kiln is not running, generated by a hot gas generator (HGG) using light oil as fuel. This is, of course, the expensive variant, and in the ideal situation, it occurs for only a few weeks during kiln overhaul. The light oil consumption in this case is approximately 200 l/h. This hot air is taken to the particle separator (pos. 491) where materials (clinker, limestone/slag and gypsum), pre-grinded on the roller press (pos. 541), are heated to extract moisture and prepare the resulting material for bag filtering.

After this, the material mixture is stored in a bin with a 70 t capacity, which is followed by a cement ball mill (pos. 561-BM1). After the ball mill, depending on the requested cement type, dust and fly ash are added. This cement is then transported via a bucket elevator to another separator (pos. 561-SR1). Particles passing through this separator compose the final product, which is transported to the cement silo (pos. 592, 593).

3. METHODOLOGY DESCRIPTION

The methodology used in the present research is based on principal of Pinch Analysis. Pinch Analysis for synthesis of optimal flowsheets, introduced by Klemeš et al. [23], simply and understandably enables discovery of a solution that is very close to the global optimum. This method is based on thermodynamic analysis of Composite Curves of process streams. As results of possible savings, capital investments and simple payback time can be calculated. Usually, super-targeting is used to obtain the optimal ΔT_{min}, but in our case, this is difficult for processing reasons. Hot meal is heated inside the kiln by flue gases in the existing process design, which cannot be heated by other process streams owing to the process design. From the other side, we have the hot clinker after the kiln that has to be cooled down rapidly, which can be accomplished by fresh air. For the present level of process equipment design, we have two limitations of the existing flowsheet that must be considered in the overall HEN design of the retrofit project. To obtain the maximum feasible heat recovery for the production process, the methodological steps were transformed as shown below.

3.1. The energy audit

Step 1. An energy audit of the existing cement production was performed to ensure mass and energy balance. Composite Curves are used for the estimation of energy consumption, recovery and efficiency of heat exchangers considering the Cross-Pinch heat transfer. Inefficient heat exchangers are identified, and process limitations and forbidden matches between heat exchangers are defined.

3.2. Setting ΔT_{min} and obtaining energy targets

Step 2. In this step, Composite Curves are built to obtain the energy target and Pinch point localisation. Here, process limitations are not considered, and thermodynamically available recovery is targeted.

3.3. Obtaining new HEN topology

Step 3. Based on the previous steps, the HEN is built considering the process limitations mentioned above. There is still Cross-Pinch heat transfer, which cannot be eliminated. Process streams with limitations are not excluded from the analysis to show the real picture of heat recovery and the future potential of energy efficiency.

Steps 2 and 3 are repeated for the full range of ΔT_{min}.

3.4. Definition of point with maximum heat recovery

Step 4. Dependences of heating and cooling demands and Pinch point localisation from ΔT_{min} are defined to find the maximum heat recovery. It is achieved by the reduction of ΔT_{min} while the hot and cold utilities are changed. The procedure defines the network temperature approach, Cross-Pinch transfer and topology concept design of the heat exchanger network.

3.5. Economic indicators

Economic indicators of retrofit realisation are determined based on the calculation of the reduced total cost of the design with the use of reduced operating and investment cost [23].

3.6. Utilisation of waste heat

This step is connected with the analysis of the potential of waste heat in the improved process. There is still a capacity for heat utilisation, and its potential should be analysed and developed. The utilisation of waste heat, which is now covered by cold utility, along with attempts to derive energy from low-potential heat sources have motivated the use of heat engines for example, by the organic Rankine cycle (ORC) [24] or utilisation of site heating demands [16]. The basics of heat integration are used for appropriate and efficient placement of heat engines. Composite Curves show the energy targets, the source and sink temperatures of heat engines and the process streams available as sources.

An intermediate utility can utilise the heat from process streams for site heating demands. This can be steam with different pressure levels, hot water, thermal oil, refrigerants, etc. The selection of the intermediate utility depends on the temperature level on which it is used. The Total Site Sink and Source Profiles should be plotted together on the T–H diagram by applying individual ΔT_{min} specifications for heat exchange between process streams to present the streams with their real temperatures [25]. In [26], the Total Site targets for fuel, turbine loads, emissions and cooling are presented. The modified Total Site targets with the use of multiple intermediate utilities for heat recovery are shown in [27]. The calculation was executed by Achilles software [28], which was developed for industrial implementations of Process Integration solutions.

4. DATA COLLECTION

The energy audit of the cement plant under study was performed during the summer operation mode. The steady-state devices, portable devices, measured process parameters needed for the study, and other data were extracted from the plant automation system. Two operation modes of cement production are considered depending on the raw mill status. If the raw mill is working, the flowrate of the cooling water in the cooling tower is 3 t/h, and a portion of the hot gases go to the raw mill for the raw material heating. If the raw mill does not work, the flowrate of cooling water in the cooling tower is increased to 11 t/h, meaning that the waste heat increases. During data extraction, 18 process streams were selected for process analysis; there are 7 hot streams and 11 cold streams. Some of the cold streams are heated by the hot stream, and this stream population forms the heat recovery component. The external heating and cooling are provided by the utility system. Cold water and ambient air are used for cooling, and heat from the fuel combustion is used as hot utility. All process streams that can be included to the process analysis are collected in Table 1.

Utility data of cement production are also provided to perform an economic analysis. The hot utility consists of different types of fuel that are fed to the kiln. Cooling water provided by the desalination plant cools the exhaust gases before the gas filters. Ambient air is also used as cold utility for the hot air cooling, which emerges from the clinker cooling stage. The hot air passes through the coolers and air filter before being discharged to the atmosphere. The total heat load discharged to the atmosphere from the air coolers is 15.6 MW in the case of raw mill operation and 19.4 MW if the raw mill is not working. All air coolers, the cooling tower and the air transporter system use fans for air blowing.

The average power consumption of the cement factory is 5.8 MW, whereas the peak load reaches 10 MW and the minimum power consumption is 1.1 MW. The main fuels used for current cement production are coal and petcoke. The current coal/petcoke ratio is 40/60 %, and the heating values of the used fuels are 25.5 GJ/t and 33 GJ/t, respectively. The price of the hot utility is 75.9 EUR/kWy, and the cold utility price is 82.0 EUR/kWy.

5. RESULTS AND DISCUSSION

5.1. Analysis of existing process

Based on the process energy audit, heat balances and stream table data, the Composite Curves of existing cement production were built considering the different operation modes of the raw mill. The Composite Curves of the existing process are shown in Fig. 1.

The Composite Curves in Fig. 2 show the energy targets of the existing cement production. The operation mode with the raw mill features heat recovery of 41,125 kW, whereas the process requires external heating of 19,397 kW and cooling of 20,225 kW. The operation mode without a raw mill requires higher utility demands as presented in Fig. 2. The energy demands increase to 22,923 kW and 24,006 kW for heating and cooling, respectively. At the same time, the heat recovery decreases during raw mill heat duty to 37,599 kW. The minimum temperature approach in the heat exchanger network of the existing process with the raw mill is 247 °C; without the raw mill operation, it is 308 °C. These values are found from existing energy targets based on audit data and heat balances. However, the real temperature approach of some heat exchangers is 1 °C because the equipment uses direct heating for example, raw mill or cement grinding. Further, in this work, the operation mode with the raw mill will be used to obtain the minimum savings. This point could be corrected later by detailed research on the operation modes to obtain results on the fluctuation of process parameters and develop a tool for operators. The significant difference between the thermodynamically grounded (see Fig. 2) and real minimum temperature approaches can be explained by Cross-Pinch heat transfer at the heat exchanger network. This is well illustrated by the Composite Curves presented in Fig. 3. Red arrows show that the heat exchangers cross the Pinch and that cold utilities are used above the Pinch point. Green arrows show the appropriate heat transfer.

The existing heat exchanger network is represented by a Grid Diagram (Fig. 4), showing the heat transfer between the process streams, but some equipment are not classical heat exchangers for example, cement grinding or raw mill. There are some heat exchangers that cross the Pinch, which increases the utility consumption and reduces the efficiency of energy usage. From the other side, this practice is a result of a design concept, which was oriented mostly on obtaining product rather than energy efficiency. This reduces the opportunities for energy efficiency at the plant operation stage as highlighted in [29]. The overview of the appropriateness of the heat transfer of the existing cement factory is presented in Table 2. It is shown that the total Cross-Pinch heat transfer is more than 20 MW, which proves the inefficiency of the existing heat system.

5.2. Maximisation of heat recovery considering process limitations

By providing a Composite Curves analysis, it is possible to obtain thermodynamically available energy targets for integrated cement production that show large potential for energy savings. Eliminating the Cross-Pinch heat transfer and cold utility above the Pinch point enables decreased utility consumption and increased heat recovery. Additionally, the minimum temperature approach can be reduced to minimize the energy targets. This situation is well illustrated in Fig. 5 by Composite Curves for ΔT_{min} = 20 °C. The targets for hot and cold utility are 4,076 kW and 4,904 kW, the heat recovery is increased to 56,446 kW. The heat recovery could be improved by 15,321 kW.

However, the cement production mostly has the process streams with solid and gas phases and other process features mentioned in part 3, and the feasibility of the retrofit project according to the energy targets shown in Fig. 5 is in question. On this basis, the heat system of cement production has significant potential for energy efficiency, but it is not easy to achieve a profitable solution owing to the process limitation connected to heating and cooling process streams No 5 and No 10. There are some process streams that have such technological features, and it is impossible to avoid it when implementing an integrated solution. Hot meal is heated from 810 °C to 1,450 °C in the kiln, and it cannot be changed using the present level of technology. The second limitation is the cooling of the clinker after the kiln to 60 °C, which must be performed quickly and is currently conducted via fans.

To find the maximum possible heat recovery of cement production considering the process limits discussed above, the dependences of the energy targets (right Y-axis) and Pinch point (lift Y-axis) from the network temperature approach were built (see Fig. 6). It is shown that the energy targets (lines 1 and 2 in Fig. 6, right axis Y) of the cement production can be reduced to a certain point (process limit), which is 50 °C. This also transforms the topology of the heat exchanger network and changes the Cross-Pinch heat. The reduction of ΔT_{min} below 50 °C is useless because it increases the Cross-Pinch heat transfer and heat transfer area while the energy consumption remains unchanged. Traditional super targeting procedure [23] does not account the process limits of, for example, as for cement production discussed above and gives a solution which is not feasible. In this case, the minimum of total cost is corresponded to ΔT_{min} = 29 °C (see Fig. 7). Nevertheless, the heat exchangers network with ΔT_{min} = 29 °C has the same energy consumption as network with ΔT_{min} = 50 °C but higher heat transfer area (Fig. 6).

5.3. *Retrofit concept design*

Based on ΔT_{min} from Fig. 6, the concept design targets of the retrofit project are obtained, including the minimum temperature approach, energy targets and Pinch point location.

The Grid Diagram shown in Fig. 8 is the concept for a new heat exchanger network of cement production with maximised heat recovery. It has additionally installed heat exchangers with a total heat transfer area of 1,555.1 m^2 and total utilised heat of 5,790.08 kW. The parameters of the new heat exchangers are presented in Table 3. The heat exchanger network shown in Fig. 8 still has high Cross-Pinch transfer of 8,850 kW. This can be considered in the future design of efficient technologies for cement production as a priority. The Cross-Pinch heat load of the retrofitted heat exchanger network is presented in Table 4.

The total investment for the heat exchanger network implementation is 256,079 EUR, including 5,000 EUR for the installation of E-114 and E-115 and 10,000 and 30,000 EUR for E-116 and E-117, respectively. The price reduction of the heat transfer area is 800 EUR, and the coefficient of area price nonlinearity is 0.87. The improvement in heat recovery leads to savings of 914,401 EUR/year assuming 8,200 operation hours per annum. The recovery period will be 3.4 months. By applying the Pinch Analysis, the total energy consumption is reduced by 2.56 GJ/t of cement production, which is 14 % less than the benchmark value. The proposed concept design of an efficient HEN shows the feasible and profitable solution for the retrofit project.

5.4. Impact and future work

Additional analysis of the integrated heat system for cement production shows the room for improvement in terms of energy efficiency on the cold utility side. The Grid Diagram of integrated cement production (Fig. 8) has shown the possibility to use the waste heat of gases, which are cooled by fan coolers. The potential of these streams could be used for power generation by applying a heat engine as mentioned in [30]. The heat load of waste gas streams is 14,338 kW with a temperature of 200 °C or higher (see Fig. 8). However, if the factory is operated in the mode without a raw mill, the generated electricity increases as well. Important points to be additionally discussed are the fluctuation of process parameters during plant operation, particles in the source streams and technical features of power generator installation.

Another option for the use of waste heat from integrated cement production is utilisation for site heating demands. There are some populated localities near the factory location in Koromač no (see Fig. 9) that could be potentially supplied by waste heat to cover their needs. The overheated water could be used as a heat carrier and could be delivered to a distance up to 10–15 km; longer distances should be additionally analysed. The maximum load of waste heat that can be utilised is 14,338 kW as mentioned above. However, the technical part, including the heat losses and pressure drop, should be calculated in detail along with the economic aspect of the retrofit project and the energy planning side.

The results of the present work have a multidisciplinary impact and further potential developments for cement production. The improved heat integration and conceptual design of a heat exchanger network could be a basic foundation for the design of efficient cement production plants and the retrofit of existing ones. This would lead to reductions in fossil fuel consumption, and CO_2 mitigation, and production cost of clinker and cement.

The utilisation of low-potential heat for site demands will help in the planning of future energy systems. Cement production can be considered as an energy source for district heating systems, power generation, etc. Nevertheless, the regions where cement production is located has to be additionally analysed with use of a system approach—for example, based on Total Site Assessment [31]—to find a feasible solution near the optimum.

6. CONCLUSION

This paper provides results that show considerable potential for energy savings in cement production. The improvement can be achieved by heat recovery in the existing process, and utility consumption can be reduced by 30 % and 29 % for external heating and cooling, respectively, which translates to lower fuel and power consumption. A retrofit of a heat exchanger network in a cement factory requires an investment of 256,079 euros with a recovery period of 3.4 months. Nevertheless, the improvement in energy efficiency can be achieved on the process design side by improving the existing process heat transfer equipment.

Coverage of the site demands is the most promising means of further improvement via waste heat utilisation and power generation by hot gases. The use of excess heat can provide a way to reduce the use of primary energy sources and contribute to global CO_2 mitigation. The results of this paper will be used for energy analysis of cement factories and provide a recommendation for decisions on efficient retrofits, new concept designs, and energy planning and strategies. Nevertheless, the technical side requires more discussion and investigation for successful implementation.

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Figures

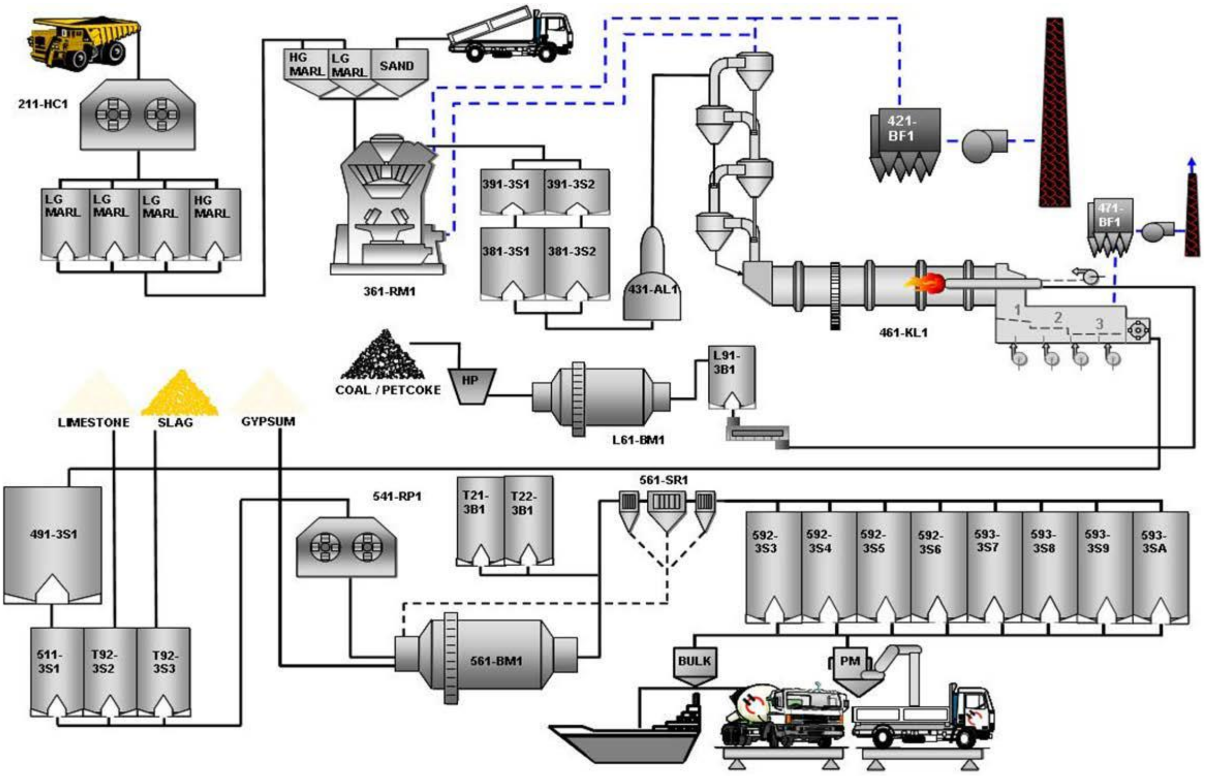

Figure 1. Principal flowsheet of cement production.

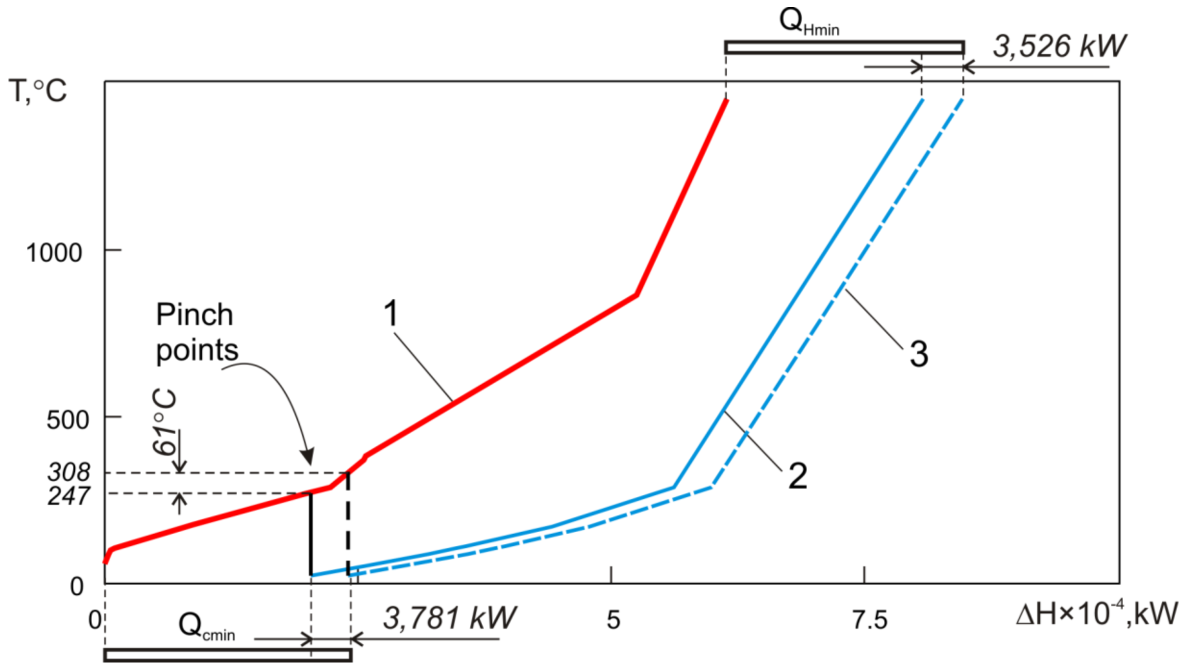

Figure 2. Composite Curves of existing cement production.
1—hot Composite Curve; 2—cold Composite Curve with raw mill operation; 3—cold Composite Curve without raw mill operation; Q_{Hmin} = 22,923 kW—hot utility demands (fuel); Q_{Cmin} = 24,006 kW—cold utility demands (cooling water, air).

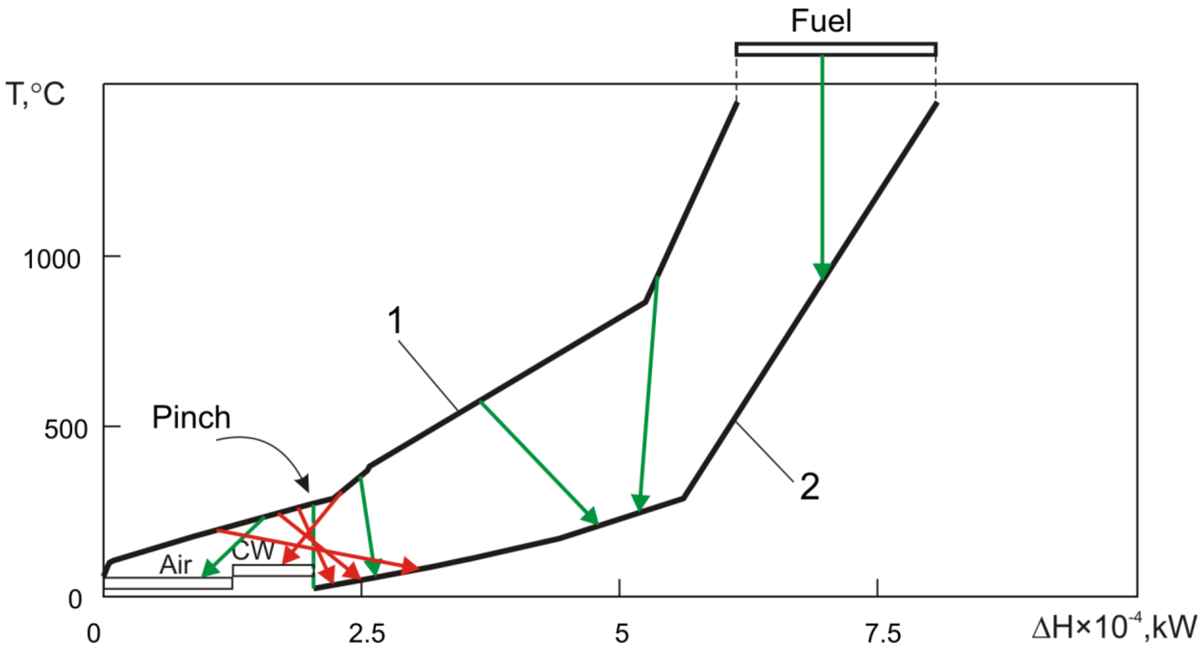

Figure 3. Heat transfer in cement production with raw mill considering the minimum temperature difference.
1—hot Composite Curve; 2—cold Composite Curve.

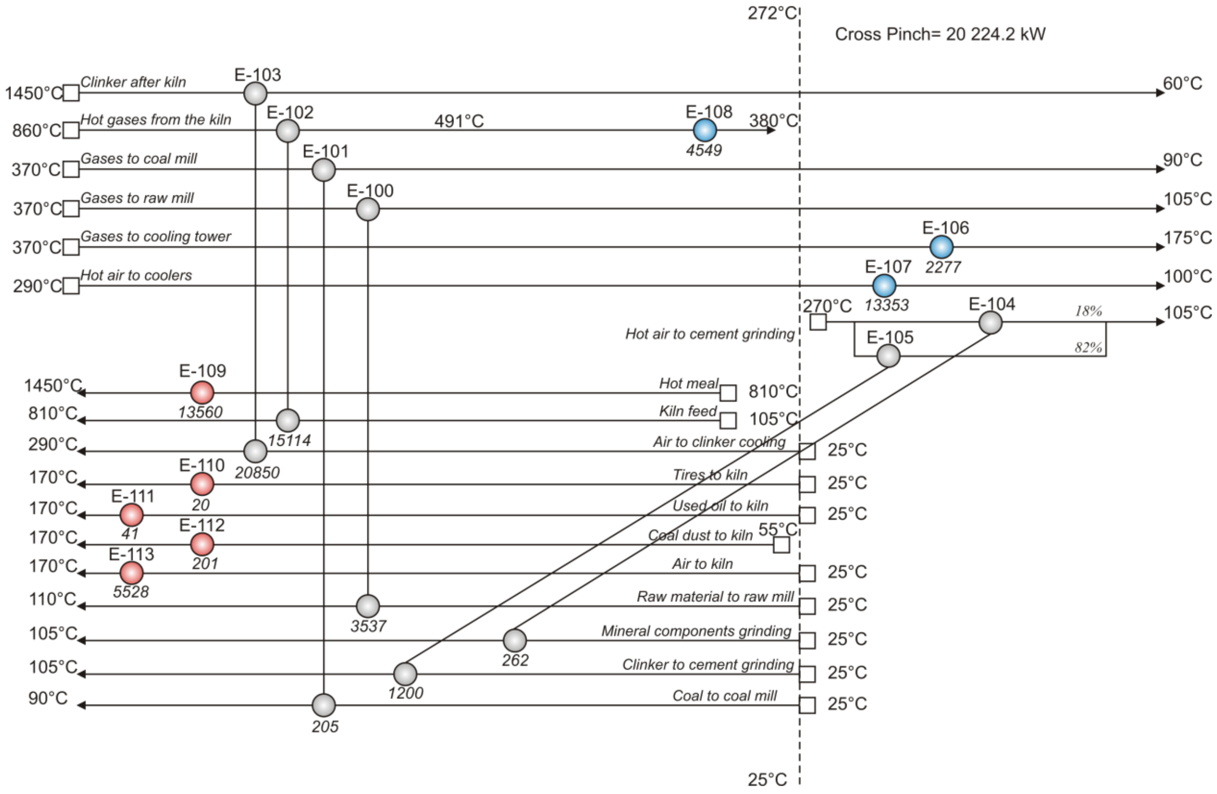

Figure 4. Grid Diagram of existing cement production.

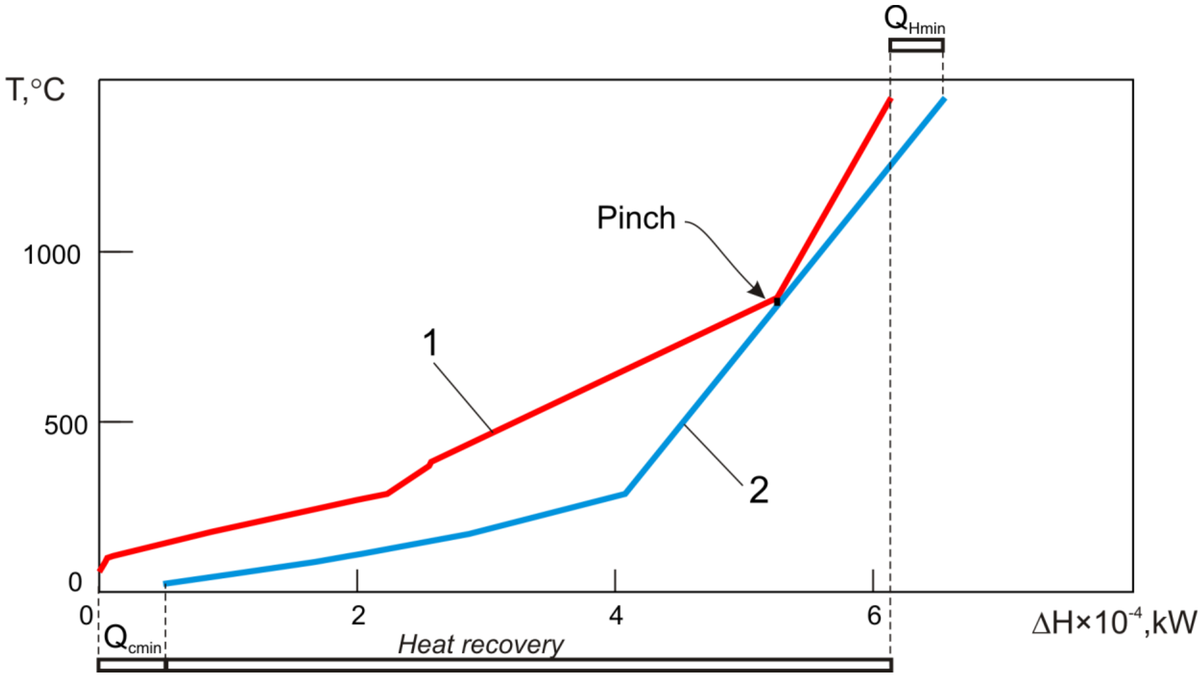

Figure 5. Composite Curves of cement production with improved heat integration. 1—hot Composite Curve; 2—cold Composite Curve with raw mill operation; Q_{Hmin} = 4,076 kW—hot utility demands; Q_{Cmin} = 4,904 kW—cold utility demands.

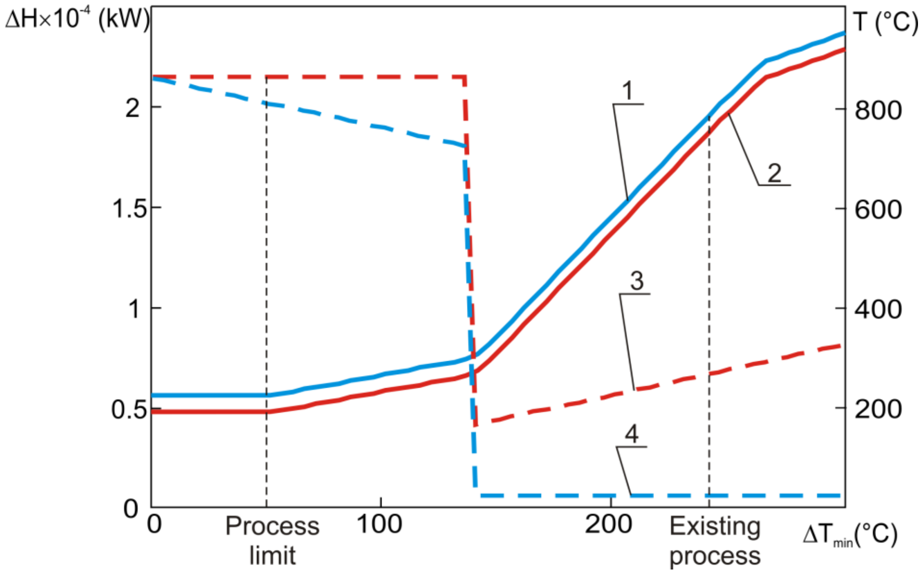

Figure 6. Definition of maximum heat recovery considering process limitations. 1—cold utility target; 2—hot utility target; 3—hot Pinch temperature; 4—cold Pinch temperature.

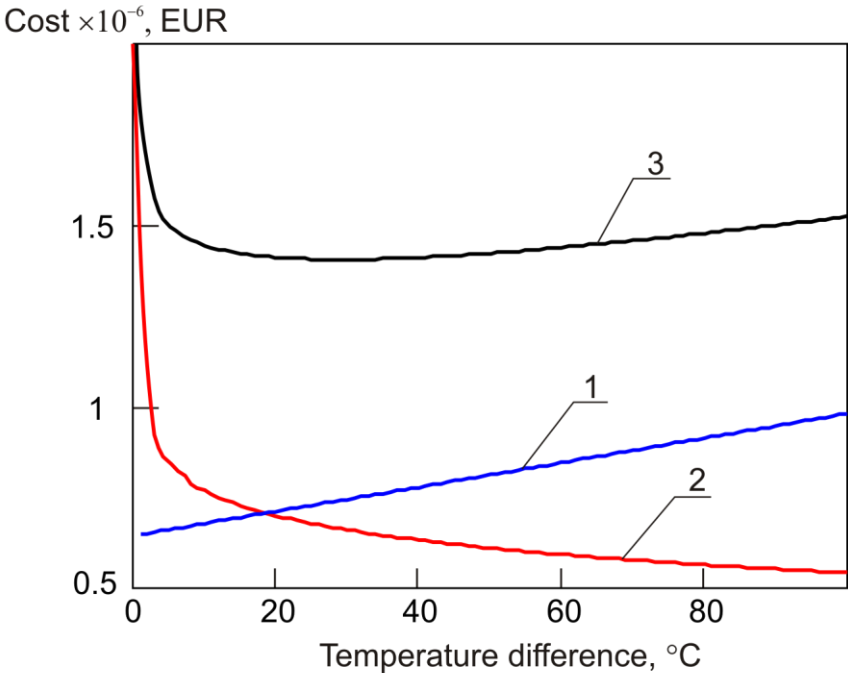

Figure 7. Super Targets of cement production. 1 – operation cost; 2 – investments; 3 – total cost.

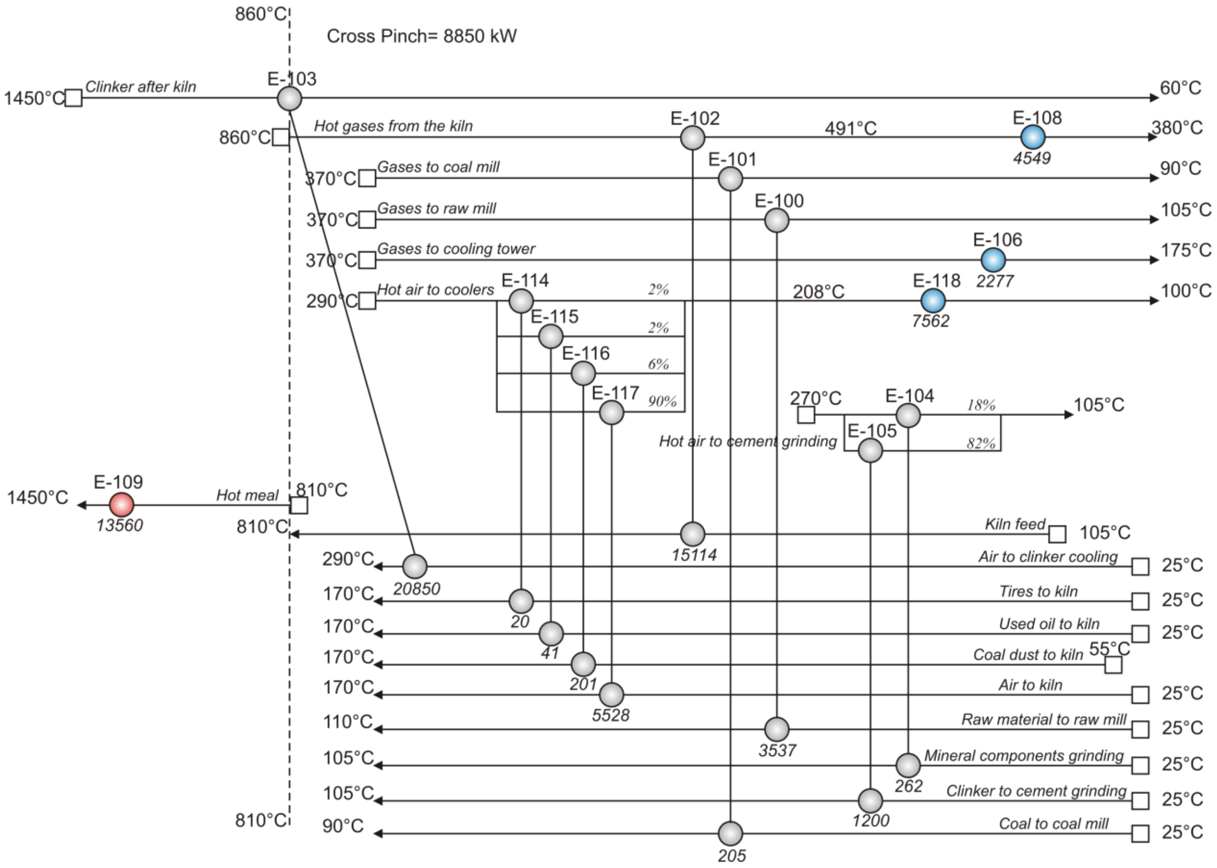

Figure 8. Grid Diagram of retrofit concept design of cement factory.

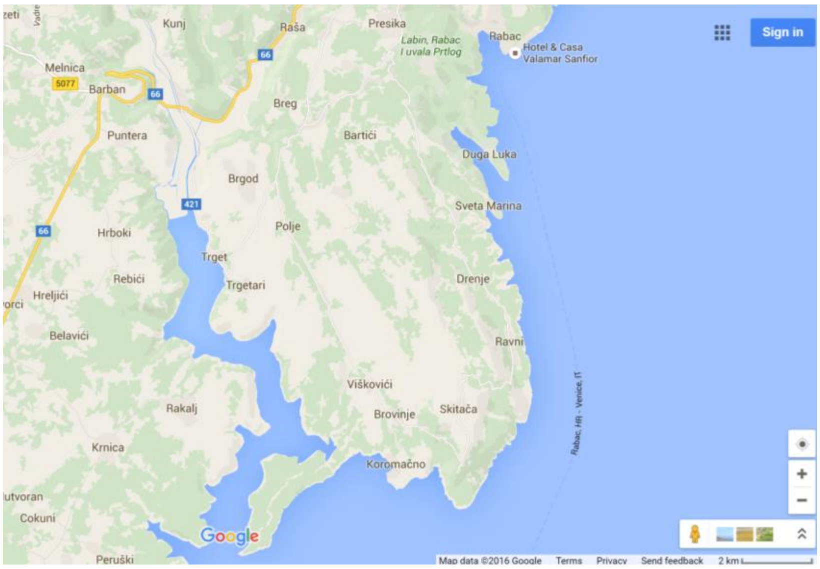

Figure 9. Cement factory location in Koromač no, Croatia (Source: Goole Maps).

Tables

Table 1. Stream data of cement production with raw meal operation

№	Stream name	Type	TS (°C)	TT (°C)	CP (kW/К)	DH (kW)
1	Gases to raw mill	hot	370	105	13.35	3,537.42
2	Hot gases from the kiln	hot	860	380	40.97	19,663.31
3	Gases to cooling tower	hot	370	175	11.68	2,276.67
4	Gases to coal mill	hot	370	90	0.73	204.75
5	Clinker after kiln	hot	1450	60	15.00	20,850.00
6	Hot air to coolers	hot	290	100	70.28	13,352.75
7	Hot air to cement grinding	hot	270	105	8.86	1,461.60
8	Raw material to raw mill	cold	25	110	41.62	-3,537.42
9	Kiln feed	cold	105	810	21.44	-15,114.42
10	Hot meal	cold	810	1450	21.19	-13,559.47
11	Coal/petcoke to coal mill	cold	25	90	3.15	-204.75
12	Coal dust to kiln	cold	55	170	1.75	-201.25
13	Air to kiln	cold	25	170	38.13	-5,528.29
14	Tires to kiln	cold	25	170	0.14	-20.30
15	Used oils to kiln	cold	25	170	0.28	-40.48
16	Air for clinker cooling	cold	25	290	78.68	-20,850.00
17	Clinker to cement grinding	cold	25	105	15.00	-1,200.00
18	Mineral components grinding	cold	25	105	3.27	-261.60

Table 2. Cross-Pinch heat load of existing heat exchanger network.

Heat exchanger	Cross-Pinch heat load (kW)
E-100	2,229.0
E-101	133.1

E-102	0.0
E-103	3,180.0
E-104	261.6
E-105	1,200.0
E-106	1,132.0
E-107	12,088.5
E-108	0.0
E-109	0.0
E-110	0.0
E-111	0.0
E-112	0.0
E-113	0.0
Network Cross-Pinch load	**20,224.2**

Table 3. Parameters of additional heat exchangers of cement production

Heat exchanger	Cold stream			Hot stream			Load (kW)	Area (m^2)
	Name	T_{in} (°C)	T_{out} (°C)	Name	T_{in} (°C)	T_{out} (°C)		
E-114	Tires to the kiln	25	170	Hot air to coolers	290	275.6	20.30	3.4
E-115	Used oil to the kiln	25	170	Hot air to coolers	290	261.2	40.48	6.7
E-116	Coal dust to the kiln	55	170	Hot air to coolers	290	242.3	201.30	39.9
E-117	Air to the kiln	25	170	Hot air to coolers	290	202.6	5528.00	1505.1
						Total	**5790.08**	**1555.1**

Table 4. Cross-Pinch heat load of retrofitted heat exchanger network.

Heat exchanger	Cross-Pinch heat load (kW)
E-100	0.0
E-101	0.0
E-102	0.0
E-103	8,850.0
E-104	0.0
E-105	0.0
E-106	0.0
E-108	0.0
E-109	0.0
E-114	0.0
E-115	0.0
E-116	0.0
E-117	0.0
E-118	0.0
Network Cross-Pinch load	**8,850.0**