Energy Science & Engineering

Open Access

RESEARCH ARTICLE

The generation of power from a cement kiln waste gases: a case study of a plant in Kenya

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Keywords
Conversion, kiln, payback period, steam generator, turbine

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Funding Information
No funding information provided.

Received: 22 June 2016; Revised: 16 February 2017; Accepted: 17 February 2017

doi: 10.1002/ese3.153

Abstract

The cement production process is energy intensive both in terms of the thermal energy (firing the kiln, drying and De carbonation) and electrical energy for driving the numerous drives within the process line. The average specific power consumption of the case study plant was 111 kWh/ton of cement with an average peak demand of 9.7 MW. The high cost of electric power at 0.14 USD/kWh results in very high cost of production that significantly lowers the company's profit margin and limits its competitive advantage. The generation of electrical power from waste heat recovery would reduce the electricity power bill through partially substituting the power procured from the national grid. This research evaluated the potential that the plant has for generating electrical power from the hot waste gases vented into the atmosphere and it was found that the plant has the potential to generate 3.4 MWh of electrical power. This results to a net potential to generate 2.89 MWh of electrical power after factoring in the auxiliary power consumption by Waste heat recovery plant system at 15%. This ultimately gave a reduction of 33% in the electricity power bill of the case study plant. The paper recommends the installation of a steam rankine cycle for the power generating plant. In this work the authors designed the steam boilers for the waste heat recovery plant for conversion of thermal energy to electrical energy, selected a commercial steam turbine and evaluated its economic feasibility and established that the designed plant would have a simple payback period of 2.7 years.

Introduction

The cement manufacturing process is an energy intensive industry, both in terms of thermal and electrical energy. The cost of energy keeps on fluctuating and this negatively impact on the manufacturing cost and eventually lowers the competitiveness and profitability of the cement industry. The energy costs in a cement industry account for about 26% of the total manufacturing cost of cement which is in the form of electrical energy accounting for 25% of the input energy and 75% is thermal energy [1]. Furthermore, the sources of thermal energy utilized in the cement industry are mostly nonrenewable and this necessitates deep consideration of energy conservation to guarantee sustainability.

The case study plant suffers financial loss as a result of higher per unit cost of power from the grid and the poor reliability of the supply. The poor reliability of supply negatively affects the kiln operations (the heart of operations) as a result of the sensitivity of the process to power quality resulting in high set up costs. This significantly raises the cost of production for the case study plant and eventually results in the loss of her competitive advantage.

The generation of Power from the cement kiln Waste Heat gases is an energy saving opportunity and it entails the recovery of the heat energy contained in the waste gases that are emitted into the atmosphere from the cement kiln. According to [2], the generation of Power from kiln Waste Heat Recovery is about conversion of the waste heat from the clinkering process into useful electrical energy. Cogeneration of power is achieved by utilizing this waste heat streams from the preheater and the cooler, passing the waste gases through boilers, which in turn generate steam which is used to turn/run turbines to generate electricity. The amount of heat energy recovered depends on several factors as stated by [3] namely the temperature of the waste heat gases, amount/volume of gases and thermal capacity of the waste gas, kiln system design and production capacity and the moisture content of the raw materials.

Most cement industries have not been able to generate power from waste heat recovery due to the high initial investment cost involved, the high energy requirement for drying the raw materials, in adequate technical competencies and fairly stable power cost. However, according to [4] and [5], power generations from kiln waste heat has become a very important venture in cement industry mainly due to fluctuating power costs, improvements in the economy of plant operations and the need to reduce power consumptions and finally strict environmental guidelines regarding reduction of CO_2 emissions [6]. The Cost of installation is considered as the main obstacle in the installation of a waste heat recovery power plant. The High the cost of a project, the less it is feasible for investors to invest.

This paper sought to determine the potential electrical energy generation from hot waste gases from the clinkering process for the case study plant, designed steam generators for conversion of thermal energy to electrical energy and evaluated the economic feasibility of the waste heat recovery plant.

This paper focuses on determining the potential electrical energy generation from waste heat recovery through actual data measured in the plant for the volumetric gas flow rates of both the preheater and cooler exit gas streams. The paper primarily applied gas handling theories and heat transfer as a basis for the heat audit across the kiln line. The knowledge and fundamental of engineering economics was employed in determining the economic feasibility of this investment through computation of the payback period.

Plant description

The case study plant has a full cement process line from mining to cement finish grinding. It has a production capacity of 1700 tons of clinker and 4000 tons of cement. The clinker produced is not sufficient to make all the required cement and therefore the plant import some clinker to meet the deficit.

The plant has undertaken several retrofitting projects in the recent past to improve operational efficiency. This includes installation of an offline pre Calciner, modification of the clinker cooler to improve on plant reliability. However, the plant still has some structural challenges that include an inefficient and short four stage preheater that limits residence time within the Calciner as well as an old cooler that limits efficient heat recovery from the cooler. The current state of the preheater limits heat transfer resulting in high gases temperatures exiting the preheater usually above (350–400)°C. This results to high specific heat consumption within the pyro processing line ranging from 900 to 950 kcal/kg clinker.

The plant is located in a relatively dry area and the raw material moisture is very low on average below 1%. This subsequently mean that the demand for drying the raw material is low and hence the high preheater exit gas temperatures has to be cooled through passing through a gas conditioning tower (GCT) before directing to the vertical raw mill and coal mill for drying the inputs. This also assists in enhancing the draught through the pyroprocessing line as the performance of the kiln induced fan improves with reduced gas temperatures.

The plant consumes on average 6.365 million units (kWh) of electrical energy per month and all of which comes from the national grid. The demand is on average 9.7 MW (peak). The average specific power consumption from mine to cement dispatch plant is 111 kWh/ton of cement. The unit cost of power is 0.14 USD resulting into an average monthly electric bill of 1 million USD as noted in the monthly power bills for the case study plant from the national power provider.

The plant produces Portland Pozzolana Cement and the product is finely ground using closed circuits ball mills to guarantee product quality with respect to achieving the target compressive strengths within a set time. The grinding department is the highest electrical energy consumer within the entire process line.

Justification

The generation of power through waste heat recovery enables the plant to reduce the electrical power bill through partially substituting the amount of power procured from the national grid. The impact of high power bills in the case study plant is depicted through

1. Increased cost of production –this reduces the profit margin
2. Reduced competitive advantage.

In addition, the poor reliability of power supply has negatively affected the kiln availability as a result of the sensitivity of the process to power quality. The heat up cost and the thermal shocks suffered by the kiln whenever there is a power outage and or a dip has over the years cost the plant huge sums of money both in terms of fuel (heating up-process set up) and refractory replacement (failure rate is high because of thermal shocks). Power interruptions constitute a plant downtime of an average 2% of total production time per annum.

It was in light of the above bottlenecks currently faced by the case study plant that the generation of power through waste heat recovery was considered a very prudent and economically viable project. It enables the plant to substitute 32.68% of its total electric power consumption and reduce the power bill by an equal margin. It also improves kiln reliability, as the power generated from waste heat recovery is sufficient to keep the sensitive part of the kiln running and cushioned from frequent power interruptions from the grid.

Results and Discussion

Gas volumetric flow rate

The volumetric flow rates of the waste heat gas streams from the cooler exhaust and the preheater exit were measured as well as their operating conditions like temperatures and the static pressures. The determination of the volumetric flow rate required the knowledge of the density of the gas stream, dust concentration, the gas temperature, the barometric pressure, and duct cross section area and gas velocity. The computation of the gas density was based on the measured volumetric gas composition. The process instruments that were used in the determination of the waste gases volumetric flow rates were Pitot tubes and "S" tube, Flue Gas Analyzer (O_2, SO_2, N_2 and CO). The velocity of the gas stream was calculated from the Bernoulli's principle.

$$P_s + \frac{ru^2}{2} = P_t, \quad (1)$$

where U = Gas Velocity; P_t = Total pressure; P_s = Static pressure; r = Gas Density.

Solving for velocity U after rearranging gives

$$U^2 = \frac{2(P_t - P_s)}{r}. \quad (2)$$

The calculated mean square velocity was multiplied by the duct cross-sectional area to get the actual volumetric flow rates. The flow rates were normalized at standard conditions and the process was repeated over a two month period and eventually an arithmetic average volumetric flow rate calculated for the two gas streams. The average measured volume of gases was 130,269 Nm^3/h at 383°C and 132,021 Nm^3/h at 332°C for the kiln preheater and the cooler, respectively. The results are shown in Tables A7 and A8 in the Appendices 6 and 7.

Thermal energy content in the cooler waste gases

The thermal energy analysis of the cooler exhaust waste gas stream was conducted and it was found that it contains 784 kJ/kg clinker of thermal energy per hour, which translated to 187.25 kcal/kg clinker per hour at 332°C as shown in Table A9 in the Appendix 8.

Thermal energy content in the preheater exit gases

The volumetric flow rate of the preheater exit gases, characterization parameters, measured gas composition and their respective thermodynamic properties were utilized in the determination of the thermal energy content of the gases exiting the preheater tower. The mean specific heat capacity of the gas stream were calculated as per the expression below and applied to the computation of the composite specific heat capacity as per the measured volumetric gaseous composition. That is,

$$Cpm = a \times (T - T0) + b \times (T^2 - T0^2)/2 + c \times \frac{T^3 - T0^3}{3} - d\left(\frac{1}{T} - \frac{1}{T0}\right), \quad (3)$$

where a, b, c, d are given thermodynamic values for different gases and materials at various temperature ranges and Cpm is the mean heat capacity. This is the expression for calculation of Cp mean of gases between temperature T and a reference temperature to [7].

The thermal energy analysis of the preheater exit gases found out that it contained 756 kJ/kg clinker of thermal energy per hour, which translated to 180.5 kcal/kg clinker per hour. The results are summarized in Table A1 in Appendix 1.

Gas conditioning tower

The preheater exit gases are passed through a GCT to lower the temperature before they can be directed to the raw mill and coal mill for drying the raw materials and passed through a bag filter for dust trappings. The hot exhaust gases enter the top section of the vertical, cylindrical-shaped and insulated tower for cooling by water injection as shown in Figure 1. The gases are drawn through the conditioning tower by a centrifugal fan.

A heat balance across the GCT was conducted and the preheater exit gases and injected water were considered as heat input to the system, whereas the GCT exit gases, the GCT bottom dust and the latent of vaporization considered as heat output.

The net thermal energy from the preheater waste gases available for power generation was the balance after accounting for the heat requirement for drying of the raw material during the grinding Process as well as for drying the coal fuel. The summarized results for the heat balance are as shown in Table A2 in the Appendix 2.

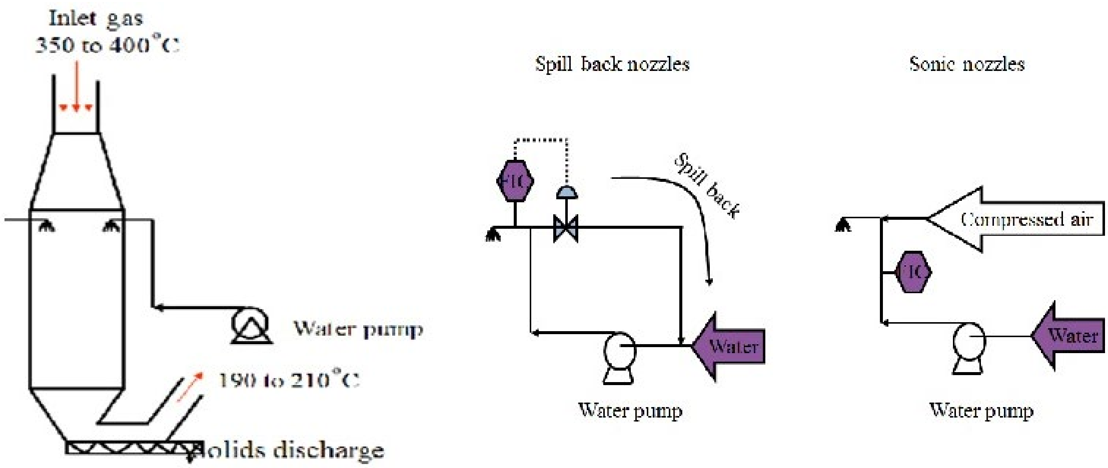

Figure 1. Schematic picture of the gas conditioning tower and water spray control mechanism.

The heat balance results in Table A2 demonstrated that 92.9 kcal/kg of clinker per hour is currently used in cooling the preheater exit gases by heat transfer into the water being injected into the GCT. The preheater waste heat recovery system is meant to utilize this heat energy by bypassing the GCT and passing this gas stream through a steam generator for power generation.

New plant layout

According to [8], the location of the preheater boiler is at the outlet of the preheater and the gas that has passed the steam boiler is returned to the existing gas duct. The best practice is to install inlet dampers into the preheater boiler that can be used for adjusting the gas volume to the Preheater boiler. The Figure 2 shows a design in which the cooler vent gases and the preheater exit gases generate steam in separate boilers that feed into one steam turbine and generator. The steam flows to a steam turbine, where it expands by decompression and thus drives a generator [9]. In the condenser the steam is cooled, condensed back to water in a recooling system and again pumped to the steam generator.

Potential electrical energy generation

It was found out that the plant had a gross capacity to cogenerate 3.4 MWh, which resulted to a net production of 2.89 MWh after accounting for the auxiliary power consumption of the waste heat recovery plant. According to [3], the efficiency of the steam turbine process is around 25–30%, meaning only a 1/4 of the waste heat is transformed into electrical energy in the cement industry.

The thermal energy content of cooler waste gases was found to be 784 kJ/kg of clinker. However, only 435 kJ/kg of clinker can be utilized for power generation. This is because the cooler boiler in the waste heat recovery plant is not 100% and the flue gases exits the cooler boiler at a temperature of 150°C. This wasted heat can be utilized by enhancing the efficiency of the cooler boiler through increasing the surface area for heat transfer (increases the capital investment) and effective lagging of the heat transfer area to minimize heat loss through conduction and radiation from the boiler surfaces.

Design of the Steam Boiler

The thermal energy balance across the preheater and cooler steam generator gave a steam production capacity of 9.744 and 10.853 tons/h for preheater and cooler boiler, respectively, at a temperature of 230°C and a pressure of five bars. The steam parameters of five bars and 230°C were based on the suitability of a commercial low parameter steam turbine (model S3-05) that was selected for the waste heat recovery plant [10].

Conducting a material balance around the boiler equipment required the definition of the system boundary. The system boundary constitutes inputs, namely; Flue gases (kg/h), raw feed water (kg/h). The output constitutes steam, which is the fundamental energy carrier (working fluid), the trapped dust constituting of the drain from the boiler bottom drum, wall losses and flue gases exiting the boiler.

Boiler features

The main features of the boiler include the economizer, the evaporator and the super heater according to [9]. The economizer is used to recover heat from the exit gas from the boiler to reduce the temperature of flue gas before venting into the atmosphere. The heat transfer is more effective if the economizer surface is large. The purpose of the evaporator is basically changing the phase of water

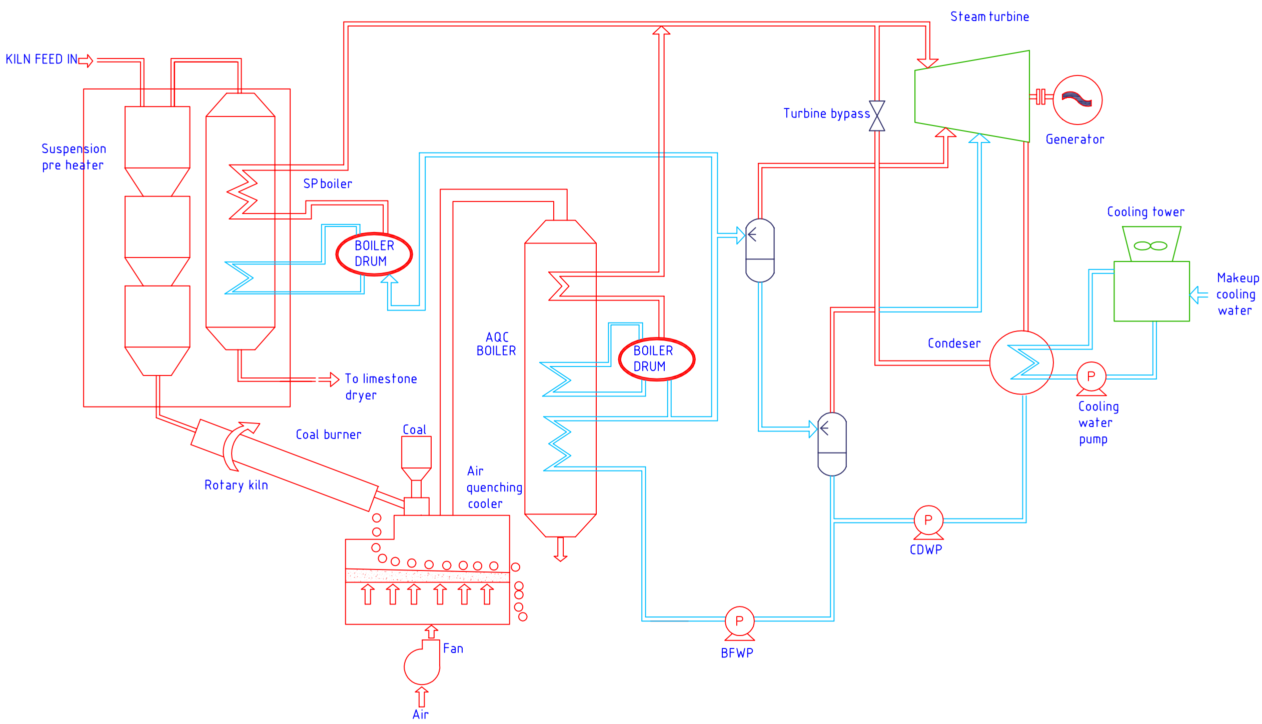

Figure 2. Rankine cycle-detailed sample schematic sketch.

from liquid to vapor, that is, evaporation. The generated steam is then transferred to the steam drum for steam/water separation by difference in density and the vapor is then transferred to the super heater. The purpose of the super heater is to provide the heat to increase the steam temperature to above saturation temperature. The heat input to the super heater is from hot flue gas as the flow arrangement is countercurrent to the flow of the working fluid for optimal heat transfer [11]. The designed waste heat recovery boiler flow diagram is shown in Figure 3.

Calculation of heat transfer areas

The computation of heat transfer surface areas required the heat transfer coefficient and the temperature differences (inlet and outlet) between the streams as per the expression below.

$$\phi = kA\Delta T_{\mathrm{lm}}, \tag{4}$$

ϕ = heat to steam, kW (thermal power) which was calculated from the steam boiler heat balance [1, 3, 4, 12].

Where k = heat transfer coefficient, W/m^2 K; ΔT_{lm} = logarithmic temperature differences; A = Required surface area, m^2.

There are three modes of heat transfer that occurs inside and outside the steam generator which involve convection, radiation and conduction and mixed heat transfer at the boundary conditions.

$$\theta_{\mathrm{ln}} = \frac{(T_{\mathrm{gi}} - T_{\mathrm{so}}) - (T_{\mathrm{go}} - T_{\mathrm{si}})}{\ln \frac{T_{\mathrm{gi}} - T_{\mathrm{so}}}{T_{\mathrm{go}} - T_{\mathrm{si}}}}; \text{countercurrent flow.} \tag{5}$$

This is the expression for getting the logarithmic temperature difference for a counter flow system where T_{gi} = Flue gas inlet temperature; T_{so} = Steam out temperature; T_{go} = Flue gas outlet temperature and T_{si} = Steam in temperature. The calculated heat transfer areas for the two boilers were calculated and summarized in Tables A4 and A5 for cooler and preheater boiler, respectively, in the Appendix 4.

Simple Payback Period

The simple Payback analysis was used to determine the amount of time expressed in years, required to recover the first cost of this project [12]. The payback period was an estimated time for the revenues in terms of fuel savings, reduced electricity bill as well as the increase in clinker output to completely recover the initial investment. The fuel savings are a result of reduced consumption of heavy furnace oil (HFO) and coal (thermal fuels) for plant set up after a power interruption. The plant set up involves preheating the kiln system to achieve the required operating temperatures for the clinkering process. According to [13], Operating & Maintenance costs for a 1–5 MW waste heat recovery plant ranges from \$0.005 to \$0.020/kWh and reflect the wide range of maintenance requirements that might be experienced. The total initial investment cost of USD 2.5 million per MW was used as recommended by [14] as well as from [15]. The auxiliary power requirement of (10–15)% of gross power generation is factored in arriving at the net power generation from the waste heat recovery power plant [14]. The simple payback period for this project based on electrical and thermal savings worked out to be 2.69 years as shown in Table A6 in Appendix 5.

Conclusion

The volumetric flow rate of the cooler and preheater exhaust gas streams was measured and thermal dynamic balance carried out to quantify the thermal energy content. The potential electrical energy that could be generated from exhaust gas streams by conversion through a Steam rankine cycle was evaluated. A heat audit was done and several heat balances carried out for the new plant layout to quantify the thermal energy content in the waste gases steam that could be recovered for power generation.

It is noted that not all gasses from the preheater exit is available for power generation as some was reserved for raw material and fuel drying. The paper focused on recovering the heat previously lost in the GCT. The paper focused on recovering the heat previously lost in the GCT. The source of thermal energy to run the waste heat recovery Power plant was purely the waste gases from the kiln and there is no other source of thermal energy that was considered in this research work.

This paper established that the hot waste gases being vented into the atmosphere from the clinkering process at the case study plant have a net potential to generate 2.9 MWh of electrical power from waste heat gas recovery which was sufficient to meet 33% of the plant's electric power demand. The designed steam generators' gave a total steam production capacity of 20.6 tons/h at a pressure of five bars and at 230°C. The required capital investment for the installation of this project was Ksh 875,500,000 with a simple payback period of 2.7 years which was considered quite attractive.

A commercial low parameter steam turbine (model S3-05) to suit the calculated optimum conditions of five bars and 230°C was selected for the waste heat recovery plant as per the data given in Appendix 4 [12].

Conflict of Interest

None declared.

References

1. Khurana, S., R. Banerjee, and U. Gaitonde. 2002. Energy balance and cogeneration for a cement plant. Appl. Therm. Eng. 22:485–494.
2. Gibbons, T. B. 2015. Waste heat Recovery in the Cement Industry. World Cement. August 13, pp. 15–24.
3. The Waste Heat Recovery and utilisation for Power Generationin a cement Plant (Phase 1). M. Sathiyamoorthy, Dr. Mazda Biglari. 4, 2012, International Journal of Advanced Research in IT and Engineering, 5:1–26.
4. Feasibility of sustainability scenarios. 2012. Harder, Dr.Joachim. ZKG, Berlin-Germany. REFRA-Kolloquium,. ZKG:1-8.
5. Nobis, R. 2009. VDZ cement international Congress, pp. 51–71.
6. Waste Heat Recovery and its Utilization for Electric Power Generation in Cement Industry. Muhammad Zeeshan, Muhammad Naeem Arbab. 1, 2015, International Journal of Engineering & Technology IJET-IJENS, 15:28–33.
7. Lafarge. 2002. Vade-Mecum Cement Process Engineering. Lafarge Canada Inc, Montreal.
8. Waste Heat Recovery Power Generation (WHRPG) for cement plants. 2010. T.Ino. [ed.] Kawasaki. Tokyo,Japan: Cement International. VDZ Congress. 8:36–45.
9. Rotich, N. 2016. Designing a Circulating Fluidized Bed (CFB). Biomass Boiler:. s.l.: www.researchgate.net.
10. QnPower. 2006. Available at http://www.qnpower.com/producthtml/152.html. www.qnpower.com. [Online]. (accessed 5 March 2016).
11. Hicks, T. G. 2006. Handbook of Mechanical Engineering Calculations. McGraw-Hill, New York, Chicago.
12. Blank, L., and A. Tarquin. 2012. Engineering economy, 7th ed. McGraw-Hill, New York.
13. Naik-Dhungel, N. 2012. Waste Heat To Power Systems, 6 pp. Combined Heat and Power Partnership, New York.
14. Productivity, Institute for Industrial. 2014. Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis. International finance Corporation, Washington.
15. CMETC. 2016. Available at www.alibaba.com/waste-heat-recovery-power-plant-in-cement indutry-manufacturers.html. www.alibaba.com. [Online] (accessed 4 April 2016)

Appendix 1: Summary thermal energy of the two gas streams

Table A1. Summary thermal energy content of the two gas streams.

Measured specific thermal energy	
Preheater gas stream	756 kJ/kg clinker
Cooler gas stream	784 kJ/kg clinker

Appendix 2: Gas conditioning tower heat balance

Table A2. Gas conditioning tower summary heat balance.

Heat input		Heat output	
Flue gas into GCT	180.4 kcal/kg clinker	Flue gas exit	92.6 kcal/kg clinker
Feed Water	6.9 kcal/kg clinker	Heat consumed by water	92.9 kcal/kg clinker
		GCT solid discharge collected at the bottom by a screw conveyor.	0.8 kcal/kg clinker
		Wall losses	1.0 kcal/kg clinker

Appendix 3: Potential power generation

Table A3. Potential electrical energy generation.

Potential electrical energy generation	
Thermal energy of preheater waste gases	756 kJ/kg clinker
% Heat requirement for drying	51.3%
Heat requirement for drying	388 kJ/kg clinker
Remainder for Power generation	368 kJ/kg clinker
Thermal energy in Cooler waste gases	784 kJ/kg clinker
Thermal energy in cooler boiler exit gases at 150°C	350 kJ/kg clinker
Thermal Energy Available for cogeneration from cooler waste gases	434 kJ/kg clinker
Total thermal energy available for electrical heat generation	802 kJ/kg clinker
Recovery Efficiency	0.2
Power generated	160.4 kJ/kg clinker 48.13 kWh/ton of clinker
Plant clinker capacity	70 tons/h
Total Gross potential power generated	3400 kWh 3.4 MWh
Auxiliary power consumption (by WHR system @15%)	0.505 MWh
Net Potential Power Generation	2.89 MWh

Appendix 4: Boilers Heat transfer areas

Table A4. Cooler boiler heat transfer surface area.

Cooler boiler	Economizer	Evaporator	Super heater
Heat to steam (Φ; kW)	574	519.9	962
Heat transfer coefficient (K; W/m^2 K)	453	246.0	205
Temperature difference (ΔT_{lm})	33	72.1	121
Heat transfer surface (m^2)	38	29.3	38.8

Table A5. Preheater boiler heat transfer surface areas

Preheater boiler	Evaporator	Super heater
Heat to steam (Φ; kW)	763.8	1107.3
Heat transfer coefficient (K; W/m^2 K)	127	542
Temperature difference (ΔT_{lm})	135	154
Heat transfer surface (m^2)	44.5	13.3

Appendix 5: Evaluating economic viability of the project

Table A6. Simple payback period.

Waste heat recovery (WHR) payback calculations		
Exchange rate, Ksh to USD	103	
Operating days per year	300	
Tph, clinker	71	
Historical Stop hrs due to power/month	14	
Kenya power supplied unit cost	14	Ksh/kWh
Item Description	Value	Units
Cost of WHRS per MW	2.5	Million USD
Gross Waste heat recovery potential	3.4	MW
Net power generation (85% of gross)	2.89	MW
Project cost estimates	875,500,000	Ksh
Expected net generation annually	20,808,000	kWh
Expected generation per month	1,734,000	kWh
Operating costs	0.02	USD per kWh
Total operating costs	50,428,800	Ksh
Revenues		
Annual Savings through improved specific power consumption(Reduced set up costs associated with firing the kiln with nil production due to persistent power interruptions	5,655,000	Set up costs
Cost of units substituted from national grid	291,312,000	Ksh
Lost opportunity, pa on clinker production (Clinker not produced due to plant unavailability due to power interruption)	78,750,000	Ksh
Total annual revenues	375,717,000	Ksh
Net revenue annually (less Operation cost)	325,288,200	Ksh
Simple pay back in years	2.69	

Appendix 6: Preheater gas volumetric flow rate

Table A7. Preheater gas volumetric flow rate.

Date	Preheater exhaust gases, Nm^3/h	Temperature (°C)	Date	Preheater exhaust gases, Nm^3/h	Temperature (°C)
17/11/2015	136,320	381	8/12/2015	130,394	387
19/11/2015	130,294	380	10/12/2015	128,477	372
24/11/2015	131,406	388	12/12/2015	127,681	374
27/11/2015	130,032	390	16/12/2015	127,029	371
28/11/2015	123,872	390	17/12/2015	130,741	370
30/11/2015	138,902	382	18/12/2015	126,874	376
2/12/2015	137,543	388	19/12/2015	132,063	379
4/12/2015	127,679	383	20/12/2015	126,051	371
6/12/2015	129,673	384	Average	130,296	383

Appendix 7: Cooler exhaust gas volumetric flow rate

Table A8. Cooler gas stream volumetric flow rate.

Date	Cooler exhaust gases, Nm^3/h	Temperature (°C)	Date	Cooler exhaust gases, Nm^3/h	Temperature (°C)
17/11/2015	129,540	350	8/12/2015	127,090	378
19/11/2015	132,896	331	10/12/2015	129,442	365
24/11/2015	133,628	316	12/12/2015	126,436	345
27/11/2015	128,220	320	16/12/2015	127,243	344
28/11/2015	128,991	376	17/12/2015	129,281	324
30/11/2015	132,412	380	18/12/2015	126,207	335
2/12/2015	127,353	303	19/12/2015	127,229	350
4/12/2015	129,045	320	20/12/2015	129,624	325
6/12/2015	131,234	335	Average	132,021	332

Appendix 8: Cooler waste gases thermal energy content

Table A9. Cooler waste gases thermal energy content.

Cooler exhaust heat energy content			
Volume measured	126,463 Nm^3/h	Mass flow rate of gases	162,194.7 kg/h
Temperature of the gas, °C	332		
Clinker production	71,000 kg/h	Enthalpy of the gas	82.0 kcal/kg
Ambient temperature, °C	26	Thermal energy of cooler waste gases	13,299,912.9 kcal/h
Altitude above sea level, m.	1532		55,686,735.3 kJ/h
Atmospheric pressure, hPa	856		
Ambient relative humidity, %	50%	Thermal energy per unit clinker production	187 kcal/kg clinker
Humidity calculations			784 kJ/kg clinker
Absolute humidity, kg H_2O/kg dry air	0.012719364		
Air moisture by mass, %	1.26%	Thermal energy of cooler boiler exhaust gases per unit clinker production at 150°C	83 kcal/kg clinker
Air moisture by volume, %	2.00%		350 kJ/kg clinker
Wet molecular weight, g/gmole wet air	28.75	Thermal energy available for power generation	435 kJ/kg clinker

Appendix 9: Commercially available steam turbine models of the required size and input [12].

NO.	Model	Capacity (MW)	Speed (*r*/min)	Inlet			Exhaust pressure (MPa)	Weight (*t*)	Overall dimensions L × W × H (mm)
				Pressure (MPa)	Dryness ()	Temp ()			
1	S1.0-0.3	1	3000	0.3		200	0.008	14.6	3220 × 2150 × 1750
2	S1.3-0.36	1.3	3000	0.36		180	0.013	18.2	4550 × 2300 × 2600
3	S1.5-0.14	1.5	3000	0.14	0.995		0.0072	18.7	3200 × 2300 × 2532
4	S1.5-0.16	1.5	3000	0.16	0.995		0.0088	18.7	3200 × 2300 × 2532
5	S1.5-1.7	1.5	3000	1.7		240	0.098	9.8	4120 × 2650 × 2530
6	S2-0.6	2	3000	0.6		275	0.0061	12	4257 × 2145 × 2375
7	S2.6-1.08	2.6	3000	1.08	0.995		0.009	17.7	3500 × 2850 × 2500
8	S3-0.5	3	3000	0.5	0.995		0.009	16	3250 × 2850 × 2500
9	S3-0.5	3	3000	0.5		230	0.009	16	3250 × 2850 × 2500
10	S3-0.5	3	3000	0.5		270	0.008	15.7	3500 × 2250 × 1750
11	S3.69-1.27	3.69	3000	1.27		300	0.007	17.7	3500 × 2850 × 2500
12	S3.9-1.08	3.9	3000	1.08	0.995		0.009	17.7	3500 × 2850 × 2500
13	S4-0.5	4	3000	0.5		230	0.01	16.3	3300 × 2840 × 2500
14	S5-1.0	5	3000	1		260	0.01	17.9	3510 × 2830 × 2485
15	S6-0.5	6	3000	0.5		230	0.01	38.1	5000 × 3900 × 2610
16	S6-0.5	6	3000	0.5	0.995		0.01	38.1	5000 × 3900 × 2610
17	S6-1.0	6	3000	1		230	0.009	42.1	5160 × 3900 × 2600
18	S6-1.0	6	3000	1	0.995		0.01	42.1	5160 × 3900 × 2600
19	S8-1.0	8	3000	1		260	0.01	42.9	5160 × 3900 × 2600
20	S8-1.0	8	3000	1	0.995		0.01	42.9	5160 × 3900 × 2600
21	S9-1.35	9	3000	1.35		310	0.005	43.2	5190 × 3900 × 2600
22	S10-0.981	10	3000	0.981		300	0.008	43.9	5200 × 3900 × 2600
23	S10-1.0	10	3000	1		260	0.01	43.8	5160 × 3900 × 2600
24	S10-1.0	10	3000	1	0.995		0.01	43.9	5160 × 3900 × 2600
25	S12-0.785	12	3000	0.785		415	0.0073	45	5205 × 3770 × 2450
26	S12-1.0	12	3000	1	0.995		0.01	42.9	5160 × 3900 × 2600
27	S12-1.25	12	3000	1.25		315	0.01	39.1	4910 × 3900 × 2600

