ENERGY AUDIT AND INTEGRATION OF WASTE HEAT RECOVERY SYSTEM: A CASE OF DIRE DAWA NATIONAL CEMENT

Kumera Beyene Fufa

A Thesis submitted to the Department of Chemical Engineering
School of Mechanical, Chemical & Material Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's
in Chemical Engineering (Specialization in Process Engineering)

Office of Graduate Studies
Adama Science and Technology University

February, 2024

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "Energy Audit and Integration of Waste Heat Recovery System: A case of Dire Dawa National Cemen**"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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Name of the student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "Energy Audit and Integration of Waste Heat Recovery System: A case of Dire Dawa National Cement" prepared under our guidance by Kumera Beyene submitted in partial fulfillment of the requirements for the degree of Masters of Science in Chemical Engineering. Therefore, we recommend the submission of the revised version of the thesis to the department following the applicable procedures.

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Major advisor	Signature	Date

APPROVAL PAGE

We, the advisors of the thesis entitled "Energy Audit and Integration of Waste Heat Recovery System: A case of Dire Dawa National Cement" and developed by Kumera Beyene, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Zelalem Tumsa (Ph.D.) ______________________ ______________

Major Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by Kumera Beyene have read and evaluated the thesis entitled "Energy Audit and Integration of Waste Heat Recovery System: A case of Dire Dawa National Cement" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Chemical Engineering

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Finally, approval and acceptance of the thesis is contingent upon submission of its final Copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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LIST OF ABBREVIATIONS AND ACRONYMS

A_{Kiln}	Area of kiln
A_{ad}	Ash conten
A_d	Air-dried moisture
Ar	As-received moisture
ASTM	American Society for Testing and Materials
CV	Calorific Value
C	Carbon
CO_2	Carbon Dioxide
CSI	Carbon Sequestration Initiative
CCS	Carbon Capturing Storage
CS	Calcium Silicate
C_2S	Dicalcium Silicate
C_4AF	Tetra Calcium Alumino Ferrite
C_3S	Tricalcium Silicate
CUSUM	Cumulative Sum
ESP	Electro Static Precipitator
EMS	Energy Management Systems
EEU	Ethiopian Electric Utility
EEA	European Environment Agency
η	Efficiency
FCad	Fixed Carbon
GHG	Green House Gas
GJ	Giga Joule
Gt	Giga tone
HAP	Hazardous Air Pollutants
HT	High Tension
H	Hydrogen
ID	Induced Draught
IEA	International Energy Agency

KF	Kiln Feed
KWH	Kilo Watt Hour
LC	Local Coal
LOI	Loss On Ignition
LT	Low Tension
M_{ad}	Moisture air dried basis
MJ	Mega Joule
Mt	Million metric ton
MP	Mega Pascal
NESHAP	National Emissions Standards for Hazardous Air Pollutants
Nm^3	Normal Meter cub
OECD	Organization for Economic Co-operation and Development
OPC	Ordinary Portland Cement
O	Oxygen
PLC	Portland lime cement
PHT	Preheater Tempreture
PPC	Portland Pozzolana Cement
Q_c	Heat of combustion
Q_{KF}	Heat of kiln feed
Q_r	Heat of formation / heat of clinker reaction
Q_{ESP}	Heat loss due to ESP
Q c, p	Heat loss through clinker
Q i, c	Heat loss due to incomplete combustion
Q w ,e	Heat loss due to water evaporation
Q p, exh	Heat loss through preheater exit gas
Q r & c	Heat loss through radiation and convection
Qs, c	Sensible heat of coal
Qs, c, a	Sensible heat of cooling air
$Q_{p,\ a}$	Sensible heat from primary Air
Q exh-pht	Preheater exit gas energy
Q exh _ cool	Cooler exhaust gas energy

RLS	Recursive Least Squares
SCM	Supplementary Cementitious Materials
SAC	South African Coal
S	Sulfur
ε	Surface emissivity
δ	Stephen Boltzmann constant
SRC	Steam Rankine Cycle
TPD	Ton Per Day
TGA	Thermo Gravimetric Analysis
T_a	Ambient Temperature
VRM	Vertical Roller Mills
V_{ad}	Volatile Matter air dried basis
WHRSG	Waste Heat Recovery System Generation

ABSTRACT

A Cement plant is an energy intensive industry both in terms of thermal and electrical energy and more than 40% of production cost is accounted for by the cost of energy. Ethiopian cement factories costs an energy of 50 to 60% of the total operational costs as contrast to global standards due to imported fossil fuel and have the problem of effective utilization of available energy within industries which affects directly the organization's profitability. The aim of this study is to conduct thermal and electrical energy audit, identify potential areas for improvement, quantify the energy losses in the system and finally propose possible energy saving opportunities in Dire Dawa National cement factory with a kiln capacity of 3000 ton-clinker per day. The energy auditing was conducted based on data collection from site measurement of material and energy flows using Infrared temperature guns , thermocouples, Air flow meters , pitot tubes with different length ,XRF, combustion analyzers and RETScreen Expert software . In this plant, Coal is the main source of thermal energy due to generation about 96.97% of the total heat input energy of system that it used for the clinker production process.

The findings revealed that around 50% of the total input energy was being lost through preheater exhaust gas (23%), cooler exhaust (13.04%), and kiln shell (14.02%) convection plus radiation. Various heat recovery methods were introduced and discussed to mitigate these losses, and it was estimated that approximately 6.63 MW of energy (equivalent to 11% of the total input energy) could be recovered using a steam Rankine cycle. Additionally, an electrical energy audit focused on the main equipment in the process unit. The audit showed that the Coal Mill and Cement Mills had achieved net energy savings compared to the baseline period. However, the Raw Mill and the Kiln exhibited a trend of energy wastage. Aligning the performance of these equipment with the baseline or best-performing historical period could result in savings of approximately 14.4 million birr.

Furthermore, the study highlighted a substantial production loss of 229,370 tons of cement over a four-year period, which equated to an estimated annual loss of 430,068,750 ETB. The findings from this study provide valuable insights into the energy performance of the Dire Dawa National Cement factory and offer recommendations for energy efficiency improvements. Implementing the proposed energy-saving measures has the potential to significantly reduce energy costs, increase profitability, and enhance sustainability in the cement industry

Keywords: Clinker, Electrical energy auditing, Energy saving ,Heat recovery, Thermal energy auditing

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the study

Cement is the most used material on a global scale and is indispensable for a wide range of buildings, infrastructure and transport systems. Cement is a binder, a substance used for construction that sets, hardens, and adheres to other materials to bind them together. Cement is seldom used on its own, but rather to bind sand and gravel (aggregate) together. Cement mixed with fine aggregate produces mortar for masonry, or with sand and gravel, produces concrete. In the time to come cement will also in many respects play an important role for modern societies and for their sustainable development.

World cement demand has been growing rapidly over the past two decades, primarily driven by infrastructure development in newly industrialized countries such as China and India. Turkey and Brazil have also played a significant role in this growth, while developed countries like the United States and Japan have experienced more modest increases but still contribute significantly to global cement production(Wang and Han 2012). The total annual cement consumption in 2016 was 4.13 Gt (Global Cement Report ,2017) and it is expected to grow up to 4.68 Gt/year by 2050 (OECD/IEA, CSI,2018) .This projection suggests that the demand for cement will continue to rise in the coming years, driven by ongoing infrastructure development projects worldwide. It reflects the importance of cement as a fundamental material in construction and highlights the need for sustainable production methods and resource management to meet this growing demand while minimizing environmental impact.

Manufacturing cement is indeed an energy-intensive process, and the cement industry consumes a significant amount of energy (Alireza Mokhtar, Mohsen Nasooti, 2020). The extensive use of energy in the cement industry leads to the generation of greenhouse gas (GHG) emissions, which contribute to global climate change. It is estimated that the cement industry is responsible for approximately 8% of global GHG emissions ((International Energy Agency, 2018), about 50% of CO_2 emissions originate from the decomposition of $CaCO_3$ in the raw material, 40% from fuel combustion, and the rest is from indirect emissions due to power consumption (Ghalandari et al., 2019). Reducing CO_2 emissions from $CaCO_3$ is a critical problem but also a great challenge, due to the difficulty of substitution of $CaCO_3$ on a large scale (Thiel and Stark, 2021). Many studies have recognized that carbon capture will be the necessary and main pathway to achieve deep decarbonization in the cement industry, especially the carbon emission from $CaCO_3$ (International Energy Agency, 2018; Fennell et al., 2021).

According to the (World Bank, 2017), energy costs typically account for 50 to 60% of the total production expenses in the cement industry, excluding capital costs. This highlights the significant financial impact of energy consumption on cement production. The pursuit of energy efficiency not only helps in reducing production expenses but also contributes to environmental sustainability by reducing greenhouse gas emissions and minimizing the industry's overall carbon footprint.

The manufacturing process of cement is indeed complex and involves various factors. It includes the characteristics of raw materials, diverse pyro-processing techniques, and the utilization of various resources. One important aspect to consider is the specific energy consumption, which refers to the amount of energy required to produce one ton of cement. The specific energy consumption can vary depending on the process used. For example, in the dry process, it typically ranges from about 3.40 Giga Joule per ton, while in the wet process, it can go up to about 5.29 Giga Joule per ton. It's worth noting that the best practice specific energy consumption in India is around 3.06 Giga Joule per ton. In some countries, specific energy consumption in cement production is even lower, measuring below 2.95 Giga Joule per ton, as highlighted in studies conducted by (Saidur et al., 2012). In industrialized countries, a typical cement plant relies heavily on fossil fuels, which account for up to 75% of the primary energy consumption. The remaining 25% is attributed to electrical energy usage. In the dry process, pyro-processing consumes a significant portion of the total fuel input, approximately 93% to 99%. Electric energy is primarily used for operating equipment involved in raw material preparation (33%) and clinker crushing and grinding (38%).

"Electrical energy is required to run Mill drives, Fans, Conveyors, Packers and for Lighting systems. Modern cement plants on an average consume about 65-75 kWh of Electrical energy for producing one ton of cement. Kiln and mills are major electrical power consuming areas of the cement plant. In fact, they are consuming about 60 % of total electrical energy requirement. When it comes to old plants due to the old technologies and some inherent barriers, the energy consumption will be in the range of 80-100 kWh per ton of cement (Parkar, Sawant, et al., 2019)."

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ton of cement. Kiln and mills are major electrical power consuming areas of the cement plant. In fact, they are consuming about 60 % of total electrical energy requirement. When it comes to old plants due to the old technologies and some inherent barriers the energy consumption will be in the range of 80-100 kWh per ton of cement (Parker, A., Sawant, R. S., et al., 2019). The variation in energy consumption within the cement industry can be attributed to several factors, including the specific technologies and equipment employed by different plants, as well as disparities in process efficiency and optimization endeavors. Coal serves as a predominant fuel source in cement production. However, the pyro-processing stage, which entails the high-temperature treatment of raw materials and clinker production, often leads to substantial thermal energy losses. Consequently, only a fraction of the energy derived from combustion is effectively utilized in the production process. This underscores the pressing need for enhanced energy efficiency measures and technologies to minimize energy losses and maximize the efficient utilization of resources.

The field of cement industry energy consumption has witnessed a significant amount of research. Many studies not only focus on energy approaches within the cement industry but also explore potential methods for improving energy consumption.

The study conducted by (Shihab Ali Khalifa, Doha Yahia Alsadig. (2019) on dry type rotary kiln system in a Cement Plant provides valuable insights into the energy consumption and potential areas for improvement in the cement industry. In their assessment, the researchers found that the total energy input required for the process was 986.87 kJ/kg clinkers, with 944 kJ/kg clinker (95.66%) obtained from coal as thermal energy. The study revealed that the energy consumption for clinker formation was 413.75 kJ/kg clinkers, with an efficiency of 42 %. This suggests that there is room for improvement in terms of energy efficiency during the clinker formation stage. Furthermore, the results indicated that approximately 41% of the total input energy was being lost through various channels. These losses occurred through hot flow gas (21.76%), hot air from the cooler stack (7.28%), and combined radiation and convective heat transfer from total kiln surface (11.71%) the kiln shell (15.11% from convection plus radiation). These findings highlight the significance of waste heat recovery and energy optimization opportunities in the cement industry. These findings highlight the significance of waste heat recovery and energy optimization opportunities in the cement industry.

In Ethiopia, the cement production sector is renowned for its substantial energy expenses, which typically account for 50% to 60% of the overall operational costs (Mulatu,D., Habte,L., & Ahn,J.W.

(2018). As the industry expands and develops, it is projected that both energy consumption and CO_2 emissions will rise. Notably, in 2010 alone, the production of cement in Ethiopia resulted in a recorded emission of 1.4 million tons of CO_2 (Tesema and Worrell 2015)

Conducting energy audits of cement industries can provide valuable insights into the current energy consumption patterns and identify areas for improvement. This study can help identify energy-saving opportunities, optimize energy use, and reduce fossil fuel consumption cost. By implementing energy-efficient technologies and practices, the industry can not only reduce its environmental footprint but also enhance energy security and contribute to the country's balance of payments by reducing the reliance on imported fossil fuels.

1.2. Statement of the problem

The cement manufacturing sector in Ethiopia faces significant challenges related to energy consumption and costs. The energy costs in Ethiopian cement factories account for a substantial portion, ranging from 50% to 60%, of the total operational costs. This is considerably higher than the global industry standards of 30% to 40% (Aklilu, 2016). The high energy costs can be attributed primarily to the reliance on imported coal for pyro processing, a crucial stage in cement production. The use of imported coal contributes significantly to the overall energy consumption, leading to increased expenses for cement manufacturers.

National Cement Share Company (NCSC) is located in the eastern part of Ethiopia, specifically at the entrance of Dire dawa city. It is situated approximately 515 kilometers away from the capital city of Addis Ababa. The history of NCSC can be traced back to 1936 G.C. when it was originally established as the Diredawa Cement & Limestone Factory. The factory was founded by Italians during the period of occupation in 1936. Since its establishment, it has been a pioneering cement production and sales facility in Ethiopia. Over the past eight decades, NCSC has played a significant role in the country's national development. As a key player in the cement industry, the company has contributed to infrastructure development, construction projects, and economic growth in Ethiopia. NCSC's location near Dire dawa city provides strategic access to transportation routes, facilitating the distribution of cement products to various regions within Ethiopia. This advantageous position allows the company to serve both local and national markets effectively.

Currently the company, operating under the Joint Venture of East African Holding and West International Holding, is offering job opportunities for a total of 1450 national and foreign citizens. These job opportunities are available in both managerial and operational occupations. Offering employment to such a significant number of individuals demonstrates the company's commitment to providing opportunities for both local and international talent. By hiring individuals from various backgrounds and skills sets, the company can benefit from a diverse work force, fostering innovation and growth. The company is facing notable energy wastage in its thermal unit operations, particularly from the kiln shell surface, preheater exhaust, and cooler exhaust. Energy is being wasted at temperatures ranging from 290°C to 390°C from the kiln surface and 350°C to 390°C from the exhaust gases. This presents a significant opportunity for energy recycling and repurposing within the factory, allowing the company to harness and utilize this wasted energy efficiently.

The company is facing challenges in the proper utilization of energy, leading to high energy bills each month. There are several primary reasons contributing to this issue:

- Absence of an energy audit team: The factory lacks a dedicated team responsible for conducting energy audits. This hinders the comprehensive understanding of energy consumption patterns and the identification of areas for improvement. An energy audit team would play a crucial role in assessing energy usage, identifying inefficiencies, and proposing energy-saving measures.
- Lack of awareness and commitment from top management: There is a lack of awareness and/or insufficient commitment from the top management of the factory regarding the importance of energy management.
- Inadequate energy management practices and employee awareness: The factory has inadequate energy management practices in place, and there is a lack of awareness and training among employees regarding energy conservation and efficient energy usage. This leads to inefficient energy consumption and a failure to identify potential energy-saving opportunities.

My decision to undertake this research is rooted in my work experience at NCSC, where I have witnessed significant thermal and electrical energy wastage due to various reasons, coupled with a lack of awareness and commitment to energy-saving practices among employees.

Because of the above reasons, the aim of this study is to assess the energy conditions of the Dire Dawa National Cement factory, identify areas where energy-saving measures can be implemented, and determine the potential financial savings associated with these measures.

1.3. Objective of the Study

1.3.1. General Objective

The general objective of the study is to conduct thermal and electrical energy audit, and propose possible alternative for energy saving opportunities in Dire Dawa National cement industry

1.3.2. Specific Objectives

The specific objectives of the research will be;

- To develop an energy audit map of the industry
- To identify areas of electrical and thermal energy wastages of unit operations
- To estimate energy saving potential of the industry
- To recommend the cost-effective methods for energy saving
- To evaluate the performance of existing operating condition with design data
- To propose waste heat integration system

1.4. Significance of the Study

The expected output of this study will identify energy wastage, provide suggested techniques which will minimize loss and reduces monthly electric bill/cost. In addition to reduced energy costs, other non-energy benefits of making energy efficiency investments can be proposed like, promote awareness in energy efficiency, improved product quality and increased productivity, reduced environmental compliance, raw material savings ,reduced emissions, extended equipment life and reduced maintenance requirements

1.5. Scope of the Study

The scope of work of the audit is to study closely the thermal and electrical energy wastages by conducting energy audit and finding energy saving opportunities in Dire Dawa National cement factory. In addition to this, the possibility of heat integration in solid gas heat exchanger unit operations including preheater tower, calciner, rotary kiln and cooler will be assessed.

The scope of the work focused mainly but not limited to the assessment and evaluation of;

- Energy supply and usage information/ energy balance
- Energy saving potential and measures (action plan and estimated time required to implement the measure recommended, amount of saving and cost of implementation)
- Financial analysis for the proposed energy saving measures and
- Energy audit reporting

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Process description

The basic process of cement production in NCSC cement factory involves Raw material preparation, clinker making in the kiln, and cement making. Each of these steps has specific energy requirements and consumption patterns, as well as various energy efficiency measures that can be applied to reduce energy use and increase productivity depending on the characteristics of and conditions at each individual cement plant. Regarding the remaining energy consumption at cement plants, it is true that activities such as final-product packaging, lighting, and building services typically account for a smaller portion of the overall energy consumption compared to the major process steps. However, it is still important to consider energy efficiency measures in these areas. This may involve using energy-efficient lighting systems, optimizing packaging processes, and implementing energy management systems to reduce energy waste in non-production areas

2.1.1. Raw Material Preparation

After the primary and secondary size reduction of the raw materials, which include limestone, rhyolite, clay, and iron ore, the next step in the process is raw material preparation. This step involves further reducing the size of the materials through grinding, classifications, mixing, and storage to achieve the required chemical composition and particle size distribution necessary to meet the desired clinker quality standards. Raw material preparation is an electricity-intensive production step, consuming approximately 25 to 35 kilowatt hours (kWh) per ton of raw material processed. The purpose of this step is to grind the raw materials into a flow able powder, which is achieved using vertical roller mills.

Vertical roller mills (VRM) used in the cement plants for grinding raw materials. These mills consist of a rotating table or bowl, which is driven by a vertical roller and the material, is fed between the table and rollers. As the table rotates, the material is ground and crushed by the rollers, resulting in the desired particle size reduction. The ground raw materials are then classified to separate the fine particles from the coarser ones. This classification process helps to achieve the desired particle size distribution. The classified materials are then mixed thoroughly to ensure a homogenous composition. The prepared raw materials, in the form of a flow able powder, are stored in homogenization silos. The moisture content in the raw material feed of a dry kiln is typically around 0.8 percent (0 percent to 0.8 percent) and approximately 1.65–1.75 t of raw meal is needed to produce 1 t of clinker (Vinci et al., 2019).

In addition to optimizing the grinding system, use of grinding aids can have positive effects on the quantitative and qualitative conditions of cement mill, and so far, different studies have been performed in this regard. The results suggested that the operational capacity of cement mills when optimizing the process conditions increased by around 9.4%, and the specific surface area of the final product rose by about 4.6% respectively compared to the case of using the grinding aid (Nasrollahzadeh, B., and Elyasi,R. 2020)

2.1.2. Fuel Preparation

Solid fuel preparation is an important aspect of the cement production process. It involves optimizing the size and moisture content of the fuel fed to the pyro processing system of the kiln. The goal is to optimize the size and moisture content of the fuel fed to the pyro processing system of the kiln, ensuring efficient combustion and minimizing energy consumption. VRM technology is employed in cement plants for grinding coal due to its high grinding efficiency. By using VRMs, the plant can achieve finer grinding of the coal, resulting in improved combustion efficiency and overall plant performance. This, in turn, leads to lower energy consumption and reduced environmental impact.

The National Cement Share Company (NCSC) uses a combination of solid fuels, primarily beneficiated South Africa coal, local coal, and biomass as alternative fuels. The infrastructure for handling and utilizing biomass as an alternative fuel is designed, constructed, and operated following best practices and industry standards. This includes ensuring proper storage, handling, and feeding systems for biomass materials. The design and operation take into account factors such as moisture content, particle size, and compatibility with the existing fuel handling infrastructure.

2.1.3. Pyro-processing

The raw material is transported to the kiln feed from the homogenizing silo. From the kiln feed bin, the materials get transported through the Bucket elevator conveyor with the measurement and control of the kiln feed rate. The pre-heating of the equipment comprises of the multi-stage cyclone system connected with gas ducts and mill chutes, the down comer duct and the induced draught (ID) fan. In cyclone pre-heater system, an efficient heat transfer takes place to finally disperse the raw material particles, when they come into contact with the hot gases from the kiln. The raw materials, which are fed into the top stage gas duct, carried by the hot gas stream into the cyclone. The material gets separated from the gas in cyclones and then travel downwards, the chute is discharged into the next lower stage gas duct. In this way, the material comes into contact with the high-temperature gases, gets pre-heated and partially calcined and then enters to the pre-calcinator. The calciner will provide sufficient residence time for the efficient combustion of the convection coal. The calciner is equipped with the multi firing points for the

Figure 2.1: National cement 3000 tpd pyro-processing unit

above-said requirements. The preheater is equipped with the ID fan for ensuring counter-current heat transfer from the kiln through the calciner and the series of cyclones. The exit hot gas from the preheater gets utilized for the waste heat energy recovery system, further drying of raw material takes place in raw mill and drying of coal happens in coal mill.

During the pyro-processing of the raw material mixture in cement production, four significant processes take place. Firstly, all moisture present in the materials is evaporated. Secondly, the calcium carbonate found in limestone undergoes calcination, resulting in the dissociation of the compound into carbon dioxide and calcium oxide (also known as free lime). The third process involves the reaction between lime and other minerals present in the raw materials, leading to the formation of specific compounds of alite(C_3S), belite(C_2S), aluminate(C_3A) and Ferrite(C_4AF) (Nuhu,S.,Ladan,S.,&Muhammad, A.U.(2020). Fourth, once the clinker is discharged to the clinker cooler from the kiln, it is cooled rapidly to minimize glass phase formation and to ensure maximum yield of alite.

Table 2.1: Technical specifications of NCSC (from plant technical data)

SNo.	parameters	Technical data
1	Calciner type	KSF
2	Kiln type	Ø 4.3 X 62 m
3	Design capacity	3000 tpd
4	Feed raw meal size	12% residue on 0.08mm sieve
5	Feed moisture	＜ 1%
6	consumption	206.60 tph
7	fuel	fuel ：coal or heavy oil
8	ratio of raw meal/clinker factor	1.5398
9	Heat consumption	750 kcal/kg clinker
10	C1 out let Air volume	680000 m^3 /hr., temp,320 ± 20 ˚C, Pressure ;-4700 pa; Dust content;100 gm/Nm3
11	Tertiary air in to calciner	Air volume～ 200000m^3 /hr.; temperature～ 850℃

The temperature of the pre-heated material would be of the order of 850°C. The raw material passes through the rotary kiln towards the flame. In the calcination zone (700–900 C), calcinations, as well as an initial combination of alumina, ferric oxide and silica with lime, take place. Between 900 and 1200 ˚C, the clinker component, $2CaO.SiO_2$, forms. Then, the other component, $3CaO.SiO_2$, forms in a subsequent zone in which the temperature rises to 1250 ˚C. At the end of this process the raw meal fed into the kiln comes out as clinker

Table 2.2: The overall sequence of cement production chemistry (Lavagna and Nisticò 2022)

Temp(˚ C)	Process Drying,	Chemical transformation
< 100	Elimination of free water	H_2O (l) → H_2O (g)
100 – 400	Elimination of absorbed water	$Al_4 (OH)_4 Si_4O_{10} \rightarrow 2 (Al_2O_3. 2SiO_2) + H_2O$
400 – 750	Decomposition of clay with formation of meta kaolinite	$Al_4O_3. 2SiO_2 \rightarrow Al_2O_3 + 2SiO_2$
600 – 900	Decomposition of meta kaolinite to a mixture of free reactive oxides	$Al_2O_3. 2SiO_2 \rightarrow Al_2O_3 + 2SiO_2$
600 – 1000	Decomposition of limestone and formation of CS & CA	$CaCO_3 \rightarrow CaO + CO_2$ $3CaO + 2SiO_2 + Al_2O_3 \rightarrow 2(CaO.SiO_2) + CaO. Al_2O_3$
800 - 1300	Binding of lime by CA & CS with formation of C_2S, C_3S, C_3A & C_4AF	$CaO.SiO_2 + CaO \rightarrow 2CaO.SiO_2$ $2CaO + SiO_2 \rightarrow 2CaO. SiO_2$ $CaO.Al_2O_3 + 2CaO \rightarrow 3CaO.Al_2O_3$ $CaO.Al_2O_3 + 3CaO + Fe_2O_3 \rightarrow 4CaO.Al_2O_3.Fe_2O_3$
1250 - 1450	Further binding of lime by C_2S to form C_3S	$2CaO. SiO_2 + CaO \rightarrow 3CaO.SiO_2$

Clinker is hard, gray, spherical nodules which formed from the chemical reactions between the raw materials. Fine grounded coal from coal mill is used for combustion in kiln and pre-calciner. During the cooling stage, the molten phase, $3CaO.Al_2O_3$, forms, and if the cooling is slow, alite may dissolve back into the liquid phase and appear as secondary belite (Ishak and Hashim, 2015).

Fast cooling of the product (clinker) enables heat recovery from the clinker and improves the product quality. During the clinker production stage, two other complementary processes are performed: fuel preparation and exhaust gas treatment. Indeed, the fuel must be milled before entering the kiln, while exhaust gases must be treated to remove dust and reduce emissions

2.1.4. Great cooler (clinker cooler)

After the formation of clinker in the rotary kiln, it is crucial to cool it rapidly to a temperature range of 70-130°C to maximize the yield of alite (tri-calcium silicate) formation, which is an essential component for cement's hardening properties. The National Cement Share Company (NCSC) utilizes grate coolers for clinker cooling with a design capacity of 3300 ton/day. Grate coolers offer several advantages in clinker cooling. They provide controlled and uniform cooling, additionally, it allows for the recovery of heat from the hot clinker. The cooling air, after passing through the clinker bed, can be utilized for various purposes within the cement plant, contributing to energy efficiency.

There are 14 cooling fans installed, likely associated with the grate coolers. The cooling air is directed through the material layer as it passes through the hole on the grate plate and the clearance between the grate plates. This airflow allows for heat exchange with the clinker, facilitating the cooling process. The cooling fans help to propel the air through the system, ensuring efficient cooling of the clinker.

A hammer crusher is installed on the discharging end. The clinker less than the pre-set size is discharged through the grizzly (less than 25mm generally), the big size clinker crushed, and the stored inside silo until it is ready to be ground and blended with other components to produce cement.

Figure 2.2: NCSC Grate cooler under maintenance on Aprl,3, 2022

2.1.5. Cement mill grinding

During the final milling phase, the clinker and additives are fed into the cement mill, where they undergo grinding to achieve the required fineness. The grinding process helps to increase the surface area of the particles and ensure proper mixing of the components. If there are any particles that have not been completely ground, they are separated in a separator and sent back into the mill for further grinding, ensuring the desired fineness is achieved. In addition to the clinker and gypsum for OPC production, various substances can be added to the clinker in the mill to produce specific types of cement. These additives may include fly ash, limestone, slag, gypsum, and pozzolana, among others. The selection and proportion of additives depend on the desired characteristics and properties of the final cement product.

Figure 2.3: NCSC cement mill grinding

NCSC operates two cement mill lines, each with a capacity of 100 tons per hour. One of the mill lines grinds the clinker with gypsum to produce Ordinary Portland Cement (OPC), which is a widely used cement type. The other mill line grinds the clinker with additives such as rhyolite and pumice to produce Portland Pozzolana Cement (PPC), which offers enhanced properties due to the presence of pozzolanic additives. The exact composition and proportion of clinker, gypsum, and additives can vary based on the specific requirements set by NCSC, applicable regulations, and the desired characteristics of the final cement products they aim to produce.

The power consumption during the grinding process is influenced by factors such as the desired fineness of the final product and the types and quantities of additives used. Once the grinding process is complete, the output of the mill is sent to cement storage silos. These silos are used to store the ground cement before it is further processed or packed. From the storage silos, the cement is then sent to the packing units.

2.2. Energy consumption scenario in cement production

The theoretical energy consumption for producing 1 kg of Portland clinker is about 1.76 Mega joules. The kiln is the major energy consumer in cement making, while most electricity is consumed in the grinding of raw materials and clinker, to produce cement. Coal and natural gas are mainly used as fuel for calcining the raw materials in the kiln, it takes about 200 kg of coal to produce one ton of cement. (Soomro, M., Tam, V. W., & Evangelista, A. C. J., 2023). Heat is lost from the plant by radiation or convection and, with clinker, emitted kiln dust and exit gases leaving the process. Most electricity is consumed in the grinding of the raw materials and finished cement. Power consumption for a rotary kiln is comparatively small, and generally around 17 and 23 kWh/t of clinker (including the cooler and preheater fans) (Alaghdefi and Latif, 2010).

In Ethiopia, Italians established the first cement factory in 1936 during the five-year fascist occupation of the Country (Getaneh, 2010). This was the Dire Dawa cement factory. Due to the rise in concrete construction in Ethiopia, the demand for cement has been growing since then and in 2008 there were four cement plants with a combined production capacity of about 2.85 million metric tons per year as reported by Ethiopian investment agency. There were about 20 cement plants in the country as of 2020 (Mulatu, D., Habte, L., & Ahn, J. W., 2018). The country's largest cement producers are Dangote Cement, Derba Cement, Mugher Cement, Messebo Cement, Habesha Cement, and National Cement with an annual production capacities of 2.5, 2.3, 2.2, 2.1, 1.4, and 1.2 Mt, respectively (Mossie, A. T., Khatiwada, D., Palm, B., & Bekele, G., 2023). As presented in Fig. 2.5, these plants contribute to about 88% of the country's annual cement production

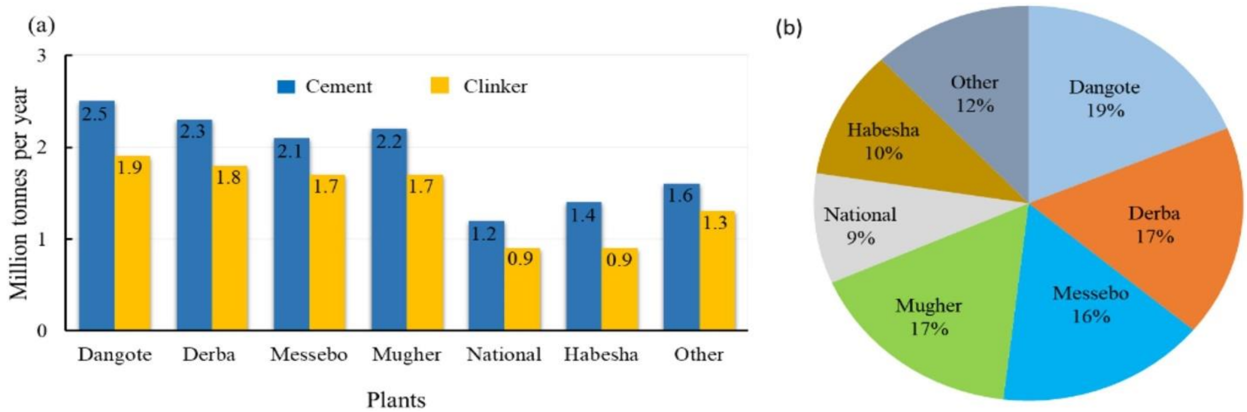

Figure 2.4: . (a) Installed cement production capacity, (b) Production share of major cement plants. (Mossie, A. T., Khatiwada, D., Palm, B., & Bekele, G., 2023)

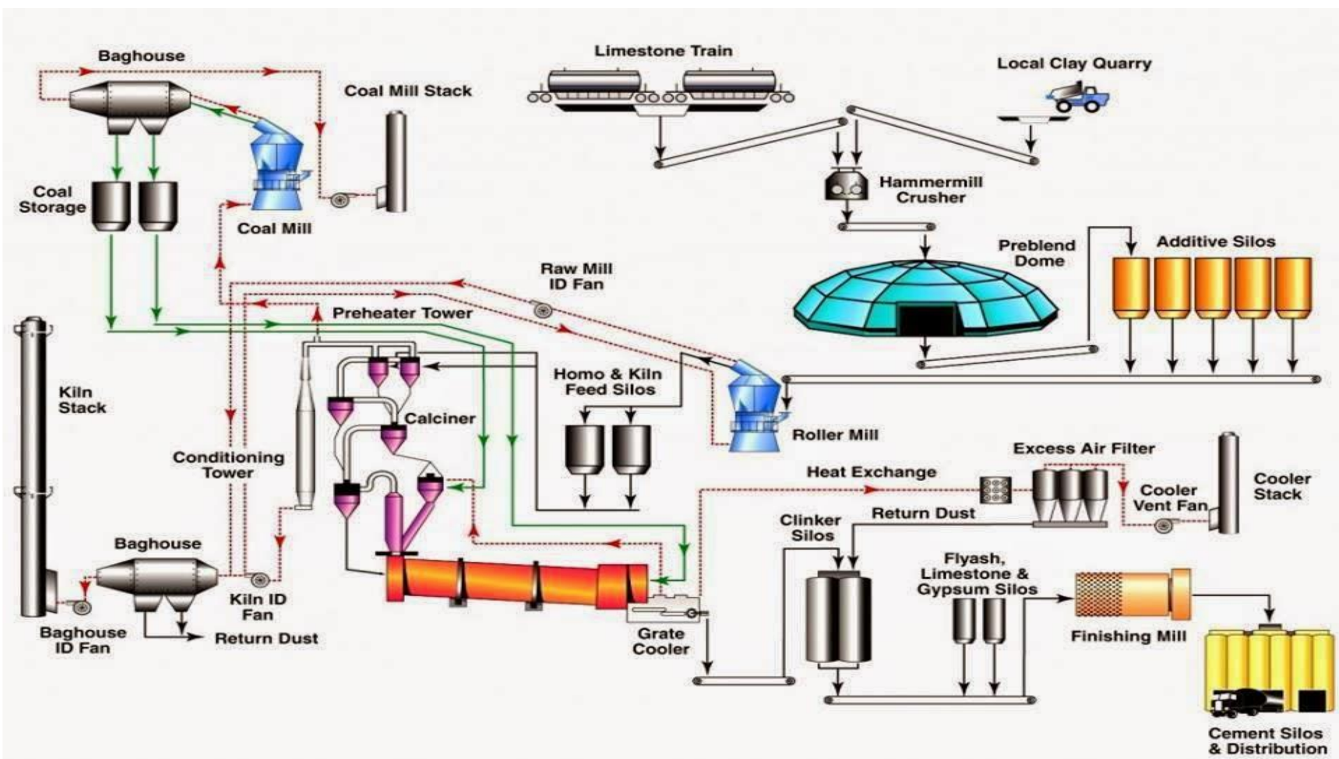

Figure 2.5: Cement production process (https://chemical-engineeringinfo.blogspot.com/2014/05/flow-chart-of-cement-industry-dry.html)

According to Gashahun (2020), Ethiopia currently has approximately 26 operational cement factories with a combined total production capacity of 26.21 million tonnes. These factories produce different types of cement, and their distribution percentages are as follows: an Ordinary Portland Cement (OPC) account for 18% of the production, Portland Pozzolana Cement (PPC) constitutes 81.1%, and Portland lime cement (PLC) makes up 0.9% of the total production.)

The use of vertical shaft kilns (VSK) in the majority of cement plants in Ethiopia has been identified as a significant challenge due to its high energy consumption, operating costs, and production of low-quality products. This issue contributes to the high production costs in the Ethiopian cement industry. However, if all the cement plants in Ethiopia were to transition to rotary kilns instead of VSK, there could be potential benefits in terms of energy savings and reduced CO_2 emissions. The adoption of rotary kilns in place of VSK could result in a fuel saving of 16% and an overall energy saving of 4% (Tesema and Worrell 2015). This transition would lead to improved energy efficiency in the cement production process, thereby reducing operating costs and environmental impact.

2.3. Typical Energy Flow Diagram at Cement Plants

Energy consumption and utilization in manufacturing cement could be generated from different sources such as electrical and thermal shown in Figure 2.5..

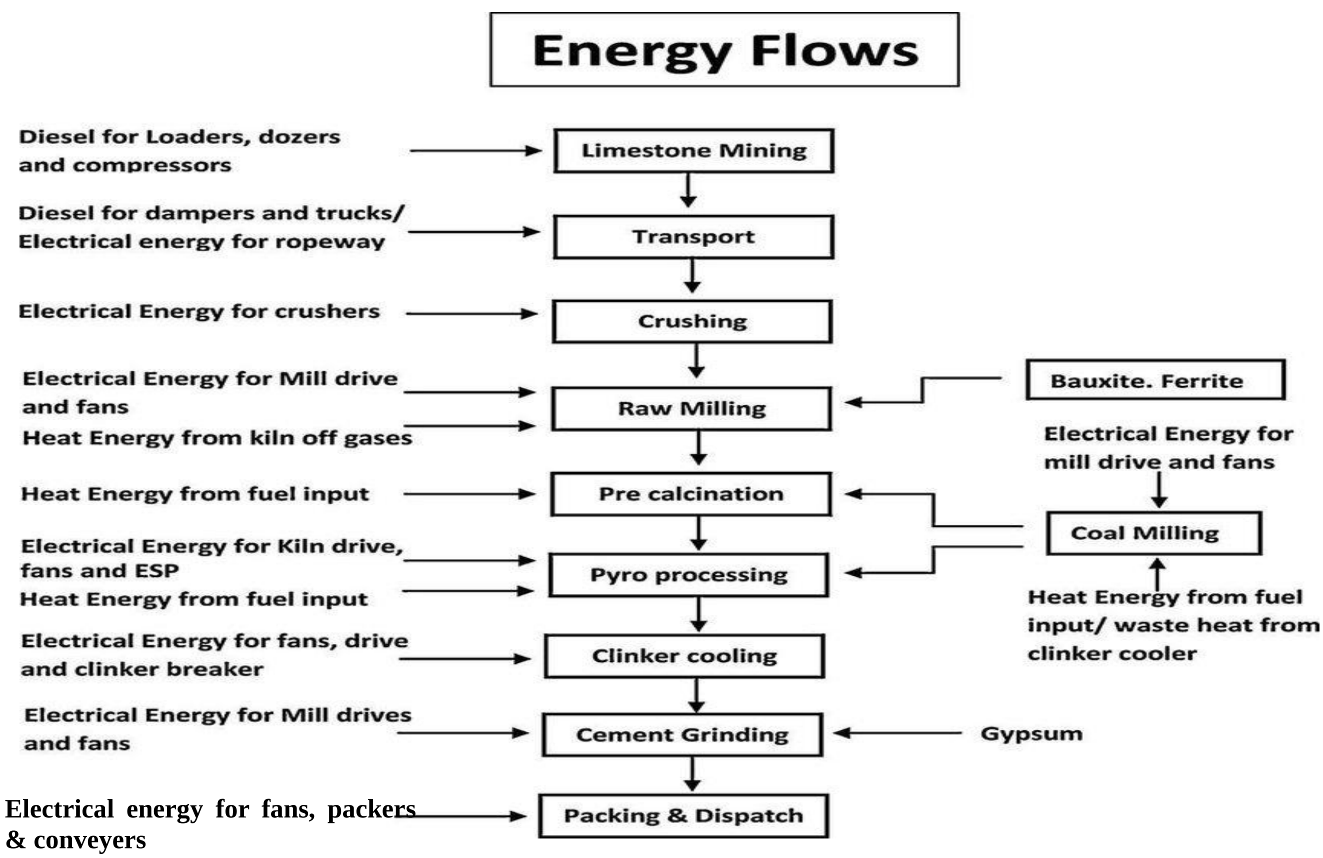

Figure 2.6: Electrical and thermal energy flow for cement production process Source: Ref. [EEA, 2010)

Specific energy use is given per unit of throughput in each process. Primary energy is calculated per ton of cement, assuming Portland cement (containing 95% clinker), including auxiliary power consumption. Primary energy is calculated assuming a net power generation efficiency of 33% (LHV).Assuming grinding of Portland cement (95% clinker, 5% gypsum) at a fineness of 4000 Blaine (Specific surface area in cm^2/gm.).

In 2019, China's cement production decreased to 2.2 billion metric tons (Gt), accounting for 54% of global cement production that year (USGS, 2020). This reduction was primarily driven by the implementation of the 2010 National Emissions Standards for Hazardous Air Pollutants (NESHAP) protocol for cement plants. To comply with these standards, many cement plants in China have installed emissions-reduction equipment. The NESHAP protocol aims to regulate and reduce emissions of hazardous air pollutants (HAPs) from cement plants. HAPs are pollutants that are known or suspected to cause cancer, serious health effects, or adverse environmental effects. In a Portland cement plant, the primary source of air toxics emissions is the kiln, where emissions originate from the burning of fuels and heating of feed materials. The pollutants regulated under the NESHAP rule for cement plants include particulate matter, organic HAPs, metals (controlled through particulate matter control), mercury, acid gases, and dioxin/furan. To comply with the NESHAP standards, some cement kilns in China have been shut down, idled, or operated at reduced capacity. This is done to ensure that emissions from the kilns are within the allowable limits set by the regulations.

Table 2.3: Energy consumption in cement production processes and process types (Worrell, Price et al. 2001)

Process step	Fuel use (GJ/ton) of product	Electricity use (kwh/ton of prod.)	Primary energy (GJ/t of cement)
Crushing	-		
Jaw crusher	-	0.3 – 1.4	0.02
Gyratory crusher	-	0.3 – 0.7	0.02
Roller crusher	-	0.4 – 0.5	0.02
Hammer crusher	-	1.5 – 1.6	0.03
Impact crusher	-	0.4 – 1.0	0.02
Raw meal grinding	-		
Ball mill	-	22	0.39

Vertical mill	-	16	0.28
Hybrid systems	-	18 – 20	0.32 – 0.35
Roller press –integral roller	-	12	0.21
Press--pregrinding	-	18	0.32
Clinker kiln	-		
Wet	5.9 – 7.0	25	6.2 – 7.3
Lepol	3.6	30	3.9
Long dry	4.2	25	4.5
short dry—suspension	3.3 – 3.4	22	3.6 – 3.7
Short dry---preheater & precalciner	2.9 – 3.2	26	3.2 – 3.5
Shaft	3.7 – 6.6	N/A	3.7 – 6.6
Finish grinding	-		
Ball mill	-	55	0.6
Ball mill/separator	-	47	0.51
Roller press/ball mill/separator	-	41	0.45
Roller press/separator/ball mill	-	39	0.43
Roller press/separator	-	28	0.31

2.4. Energy optimization and approaches

There has been a significant research focus on energy saving and optimization methods in the cement industry (Aklilu, 2016; Gudise, 2015). Researchers and experts have been exploring various strategies and technologies to reduce energy consumption and enhance the overall efficiency of cement production.

Some key areas of research and development in energy-saving and optimization methods in the cement industry include:

- Alternative Fuels and Raw Materials: Investigating the use of alternative fuels, such as biomass, waste-derived fuels, and alternative raw materials, to replace traditional fossil fuels and reduce greenhouse gas emissions. This approach aims to optimize the combustion process and improve energy efficiency.

- Process Optimization: Developing advanced process control techniques, modeling, and simulation tools to optimize various stages of cement production, including raw material preparation, clinker production, and cement grinding. These methods aim to minimize energy losses, improve process stability, and enhance overall productivity.
- Waste Heat Recovery: Implementing waste heat recovery systems to capture and utilize the excess heat generated during cement production. This recovered heat can be used for various purposes, such as preheating combustion air, generating electricity, or supplying heat to other parts of the plant.
- Clinker Reduction: Exploring alternative cementitious materials and supplementary cementitious materials (SCMs) that can partially replace clinker without sacrificing the quality and performance of the cement. This approach helps reduce the energy-intensive clinker production and associated carbon dioxide emissions.
- Energy Management Systems (EMS): Implementing EMS to monitor, measure, and analyze energy consumption and production in real-time. It also to identify energy-saving opportunities, optimizes energy use, and track performance indicators for continuous improvement.
- Technology Upgrades: Investigating and adopting advanced technologies and equipment, such as high-efficiency grinding systems, optimized kiln designs, and improved heat recovery systems, to enhance energy efficiency and reduce environmental impact.

These research efforts aim to address the challenges of energy consumption and environmental impact in the cement industry, promoting sustainability and enabling the industry to meet its climate and energy targets.

The three different approach of energy saving strategies in industrial sectors are:

- Energy savings by management: Energy management is the strategy of meeting energy demand when and where it is needed. This can be achieved by adjusting and optimizing energy using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems. There are many types of energy saving by management such as: i) Energy audit, ii) Energy efficiency courses and training program, and iii) Housekeeping.

- Energy saving technologies: Applications of technologies have tremendous potential to reduce industrial energy use. Industrial energy use can also be reduce using variable speed drive (VSDs) in motor operated system, high efficient motors (HEMs), efficient nozzles in compressed-air system/ leak prevention, waste heat recovery system in boilers etc.
- Energy saving by policies/regulations: Energy Policy is the manner by which a given entity (often governmental) has decided to address issues of energy development including energy production, distribution and consumption.

The attributes of energy policy including legislation, international treaties, incentives, agreements, guidelines, taxation, energy efficiency standards, and energy guide labels. These policy measures are designed to promote energy conservation, enhance energy efficiency, and incentivize investments in sustainable energy technologies. By implementing energy-saving technologies, significant benefits can be realized in terms of electric energy savings, emissions reduction, and utility bill reduction in industrial sectors. The adoption of energy-saving technologies in industry has proven to be economically viable in many cases. Through energy audits and assessments, specific energy-saving measures can be identified and evaluated for their potential impact and economic feasibility. These measures may include upgrading equipment, optimizing processes, implementing energy management systems, and adopting energy-efficient practices. Payback periods for different energy savings measures have been identified and found to be economically viable in most cases

2.4.1. Energy audit

Energy audit is the key to a systematic approach for decision-making in the area of energy management. It attempts to balance the total energy inputs with its use and serves to identify all the energy streams in a facility. It quantifies energy usage according to its discrete functions. It is the process of assessing the way energy is being used and possibly wasted in industries, energy consuming systems, machines, etc. and if wastage is found, it takes corrective measures to minimize the wastage. Minimization of energy wastage is done by finding better way of meeting the energy demand.

2.4.1.1. Importance of energy audit

In any industry, the three top operating costs are often found to be energy (electrical and thermal), labour and materials. Among the three, energy has the highest potential for cost reduction.

Energy audit will help to understand more about the ways energy is used in the industry, and help in identifying the areas where waste can occur and where scope of improvement exists .Such an audit program will review variations in energy costs, availability and reliability of supply of energy, decide on appropriate energy mix, identify energy conservation technologies, retrofit for energy conservation equipment's etc.

Energy audit can be classified in to the following types: Preliminary audit, targeted energy audit and detailed audit

- Preliminary Energy Audit (walk-through): Provides a basic assessment of energy consumption and identifies low-cost, no-cost measures for energy savings. Involves a visual inspection of the facility, identification of energy-consuming equipment, and general recommendations for improvement.
- Targeted Energy Audit: Focuses on specific energy-consuming systems or areas of the facility. It involves a more detailed analysis of energy consumption and performance of targeted systems, such as lighting, HVAC, or compressed air.
- Detailed Energy Audit: A comprehensive and in-depth assessment of energy consumption and efficiency throughout the facility. It involves extensive data collection, measurement, and analysis of energy use, equipment performance, and operational practices. Provides detailed recommendations for energy efficiency improvements, including technical specifications, estimated energy savings, and financial analysis.

These classifications reflect the varying levels of detail, scope, and analysis involved in different types of energy audits. The choice of the appropriate audit type depends on factors such as the goals of the audit, available resources, and the complexity of the facility's energy systems.

2.4.1.2. Energy Audit experience

Nowadays, many energy audits have been carried out in different factories around the world, and the results of these investigations have been published

In Germany, energy audits have been recognized as a valuable tool to overcome barriers and enhance energy efficiency. Energy audits help in obtaining crucial information about energy consumption patterns and evaluating energy-saving opportunities (Foladori *et al*., 2015). By conducting audits, companies and policymakers can gain insights into their energy usage, identify areas for improvement, and develop effective energy management strategies. The European Union has conducted surveys on industrial energy audit programs in various countries. The purpose of these surveys is to gather information and present effective energy audit practices to policymakers (Ferdnando and Lin, 2017). By sharing best practices and successful case studies, policymakers can develop informed policies and initiatives to promote energy efficiency and encourage companies to conduct energy audits. In China, research has been conducted on energy audit guidelines and policies. The findings indicate that energy audits have been instrumental in assisting companies in optimizing their energy management structure. Energy audits help companies recognize energy conservation opportunities, identify areas of improvement, and develop strategies to reduce energy consumption (Oyedego *et al*., 2016). By implementing energy audit recommendations, companies in China can enhance their energy efficiency and contribute to sustainability goals.

These studies highlight the positive impact of energy audits in providing valuable information, optimizing energy management practices, and identifying energy-saving opportunities. Energy audits serve as a foundation for informed decision-making and the development of effective policies and strategies aimed at improving energy efficiency and reducing energy consumption. By promoting energy audits, countries and organizations can take significant steps towards achieving their energy and sustainability targets.

Many researchers have focused on assessing the thermal energy situation during clinker production and identifying potential energy-saving measures and cost-saving potentials through detailed energy audits. Conducting such audits can provide valuable insights into the energy performance of the clinker production unit and help in optimizing energy consumption. Here are some key areas that researchers typically investigate during energy audits of clinker production: By conducting detailed energy audits of clinker production units, researchers can provide valuable recommendations for optimizing energy consumption, reducing energy costs, and improving overall energy efficiency. These findings can be utilized by industry practitioners and decision-makers to implement energy management strategies and drive sustainable practices in clinker production.

Ghalandari, V., Majd, M. M., & Golestanian, A. (2019) conducted research on the pyro-processing unit of a cement plant in Iran to improve the efficiency of the clinker production process and operating the system. The plant has a capacity of 3300 ton/day of clinker with specific energy consumption of 1723.8Kj/kg clinker. The results of the energy audit showed that about 50% of total heat input was consumed for the clinker formation and 48% of it was lost in the form of radiation from the shell of the kiln, grate cooler, preheater, and the potential of electrical energy production from the exhaust gases of preheater and grate cooler was evaluated through the waste heat recovery power generation (WHRPG) unit. It was found that about 5.2 MWh power can be produced in WHRPG unit convection along with exhaust gases from the pyro-processing unit. The exhaust gases and kiln shell heat losses accounts for 27.9% and 11.97% of the total heat input, respectively. The energy audit team concluded that using waste heat recovery steam generator and secondary kiln shell will save 42.88MWh/year, and reduction of 14.10% of greenhouse gases can be achieved

Verma, Y. K., Mazumdar, B., & Ghosh, P. (2021) conducted thermal energy audit of Emami Cement Limited, Baloda Bazar, Chhattisgarh, India with clinker production capacity of 320,000 ton per year and the results of the energy audit showed that energy efficiency during clinker formation was 58.67%. Unidentified losses of 5.74% were observed for the system. The energy of 16.34% was conserved by using the waste heat recovery system for electricity generation and 1.15% was conserved by using the pyro jet burner and gunning cast able of 250 mm as per our design data for the cement production unit. Overall, 75.17% of heat was utilized during the process and 24.83% was lost through stack and other activities

Madlool et al. (2013) conducted a study revealing that the cement industry has the capacity to achieve a significant energy saving of up to 3.4 GJ per ton, along with a remarkable reduction in CO2 emissions by 212.54 kg per ton.

The energy consumption of the dry cement manufacturing process was examined through a study conducted at the Keman cement plant in Iran. The findings revealed that the system's efficiency was measured at 46.6%, which is lower than the expected levels. To tackle this issue, the study recommended the implementation of a waste heat recovery steam generator. This system would capture the heat loss from the kiln exhaust gas, which maintains an average temperature of 315°C, as well as the air discharged from the Cooler stack at an average temperature of 215°C. The estimated potential for this waste heat recovery system was approximately 500 kW, and it was projected to have a payback period of 11.28 months (Gholipour Khajeh, Iranmanesh, & Keynia, 2014).

Thermal energy audit of a horizontal rotary kiln system was conducted, which has been using in the Van Cement Plant in Turkey. The plant has a capacity of 600 ton/day of clinker with specific energy consumption of 3.68GJ/ton-clinker (Shen *et al*., 2012) As per collected data from the plant and complete energy balance for kiln system, It was found that about 40% of the total input energy was being lost through hot flue gas (19.15%), cooler stack (5.61%) and kiln shell (15.11% convection plus radiation). Some possible ways to recover the heat losses are also introduced and discussed. For the first two losses, a conventional WHRSG system is proposed. Energy balance calculations showed that 1 MW of energy could be recovered. For the kiln surface, a secondary shell system has been proposed and designed. It is believed that the use of this system would lead to 3 MW of energy saving from the kiln surface. Hence, the total saving for the whole system has been estimated to be nearly 4 MW, which indicates an energy recovery of 15.6% of the total input energy with a payback period for the two systems is expected to be less than 1.5 yr. A similar study by *Tripathy, S.C., Roy, M., & Balasubramanian, R. (1992)* showed that the efficiency value for the kiln system was found to be 41.83%. The major heat losses for the system were identified as the preheater exhaust gases and heat carried away by cooler vent air (grate cooler). The preheater exhaust gas carries about232962 m3/hr. Which indicate the total energy recovery from these waste gases of (16.48%). A waste heat recovery steam generation system was selected showing the energy saving potential of 1.14 MW from the waste heat streams with simple pay back of 48 months.

A Portland cement plant in North East of Nigeria energy audit was carried out. The plant has capacity of 800,000 ton/year. The auditor revealed that the kiln unit has thermal efficiency of 41%, whereas international standard is 51-54%. The exhaust gases and kiln shell heat losses accounts for 27.9% and 11.97% of the total heat input, respectively. The energy audit team concluded that using waste heat recovery steam generator and secondary kiln shell will save 42.88MWh/year, and reduction of 14.10% of greenhouse gases can be achieved (Kabir, G., Abubakar, A. I., & El-Nafaty, U. A. , 2010)

A complete thermal energy auditing in Messebo cement factory in Ethiopia by (Gebreslassie, M. G., Gebrelibanos, K. G., & Belay, S. (2018) shows that the actual energy consumption for clinker formation is around 419.4 Kcal/kg-cl, which is nearly 45.83 % of system efficiency, below the expected efficiency of modern plants that is in the range of 50-54 %. The major heat losses for the processes were identified as the pre - heater exhaust gases and grate cooler vent air that accounted as 199.3 kcal /kg (21.78%) of clinker and 176.7kcal/kg (19.31%) of clinker respectively. In this case hot air from cooler stack and pre-heater exhaust gases has been considered as potential for the heat recovery. The heat loss through kiln surface is 4.1 % (radiation & convection). Comparison of the specific heat consumption of the system (844.5 kcal/kg of clinker) with the standard specific heat consumption (730-780 kcal/kg of clinker) showed that there are huge energy losses in the kiln system.

Finally researchers proposed energy improvement mechanisms for the system by applying proper operational control, optimization of air in kiln and cooler, changing worn out bricks to protect the losses though convection and radiation from the kiln surface and other energy saving techniques. A similar study in the same plant was done by (Beniam, 2019; Tashin and Vedat, 2004) specifically on Line-1 with a capacity of 200t/d. The audit result shows about 41% of the total input energy was being lost through hot flue gas (19.53%), cooler stack (16.22%) and kiln shell (5.27% convection plus radiation). The final out let temperature of hot gas is high after using the flue gases for pre-calcination and pre-heating of raw materials .In this case a researcher proposed that WHRSG should be installed. In order to minimize the heat lost from the kiln shell, secondary shell system is applied and added on to the kiln surface, the anzast layer inside the kiln bricks lining should have to be maintained and also the kiln surface should have to be painted for proper emissivity. By using these systems about 3.5 MW of energy is saved from the kiln surface which means 9% of the total input energy is recovered.

Saidur et al., (2009).Studied energy consumption, savings and emission reductions for industrial motors in Malaysia by using different energy savings strategies including VSDs, capacitor banks to improve the power factor, by regular maintenance of electric motors and implementing energy efficiency regulations. Authors estimated about 56,329 Mwah/year, 93,453 Mwah/year, 104,975 Mwah/ year of energy can be saved for 20%, 40% and 60% speed reduction, respectively. Authors also estimated about 3,604,995 US$/year, 5,981,015 US$/year and 9,718,400 US$/year can be saved as electric bills for 20%, 40% and 60% speed reductions, respectively .

Similarly motors operated at different load factors in Indian cement factory was conducted (ICR, 2013); the result shows that some of motors are operated at (3-16%) of their full load. These low loads can be optimized with the application of variable speed drives (VSD) to match the load requirements.

Therefore application of VSD can be considered as a potential solution to optimize motors load to avoid energy wastage by these motors. Based on the study results; it has been found that about 1,865,925 Mwah/year of energy can be saved for low tension (LT) motors for 60% speed reduction and 2,122,675 tons/year of CO2 emission could be avoided and about 4,600,386 Mwah/year of energy can be saved for High Tension (HT) motors for 60% speed reduction using VSDs. The average payback period (PBP) for implementing VSDs for LT and HT motors found to be very low (i.e. about 2 days). In this particular study it is observed that installing both LT and HT capacitors to improve power factor found to be not economically viable owing to low level of energy savings

All those researches showed that there is huge amount of energy losses (thermal and electrical) during cement production. For this reason, appreciable amounts of thermal energy could be saved or conserved by preventing leakage of heat and making heat recovery in the kiln, pre-heater and grate cooler by modifying the equipment and electrical motors could be saved by regular maintenance, replacing VSD and create awareness towards energy conservation throughout the manufacturing processes. Industrial energy audit is therefore the key to quantify all the energy streams in the facility and quantifying energy usage according to its discrete function. In short, the audit is designed to determine where, when, why and how energy is being used. It allows a better assessment of the heat consumption and the potential for improvement by identifying opportunities to improve efficiency, decrease energy costs and reduce greenhouse gas emissions that contribute to climate change

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Materials

During the detailed energy audit, a combination of instruments and software tools, including the RETScreen software tool, was utilized to measure various parameters and gather accurate data for analysis and evaluation. These tools played a crucial role in collecting reliable information to assess energy consumption and identify potential areas for improvement. The specific instruments used, along with the RETScreen software tool, included:

Infrared Temperature Guns: These tools were used during the energy audit to measure the surface temperatures of key components in the cement plant, including the kiln, precalciner, cyclones, cooler, and ducts. These tools work by detecting thermal radiation emitted by objects and are particularly useful for non-contact temperature measurements (Schachenhofer, E. 2007).

Thermocouples: These tools were used to measure temperature at specific locations within the plant. Thermocouples are reliable sensors that convert temperature into an electrical signal.

Power Meters: Power meters were employed to measure electrical energy consumption. They provide insights into the energy usage of equipment and processes.

Air Flow Meters: These instruments measure the flow rate of air within ducts or pipes of preheater /exhaust gases. They help assess the performance of ventilation systems and quantify air movement in critical areas.

Pitot Tubes: Various pitot tubes with different lengths were used to measure fluid velocities, particularly in gas streams. They enable the determination of flow rates and the evaluation of energy losses in ducts or chimneys.

Differential Pressure Gauges: These gauges measure the difference in pressure between two points. They are utilized to assess pressure drops across filters, fans, or other components, which can indicate energy losses or inefficiencies.

Length and Distance Meters: Instruments for measuring lengths and distances were used to accurately determine dimensions and sizes of equipment, ducts, or other structural components relevant to the energy audit.

Combustion Analyzers: These analyzers assess the composition of flue gases, including oxygen, carbon dioxide, and carbon monoxide, to evaluate combustion efficiency and identify potential improvements installed at kiln inlet and preheater exhaust gas (Irin, N. A., Arju, J. O., Sakib, F. S., Ishmam, S. A. S., & Arnob, A. R., 2020).

Bomb Calorimeter: A bomb calorimeter was utilized to determine the calorific value of coal fuel or other combustible materials (biomass). It helps evaluate the energy content and quality of fuels used in the cement plant (Balachandar, V., Ramkumar, T., Kalidasan, B., & Subramaniyan, C. 2021)

Coal Proximate analyzer (TGA) : specialized instrument used to determine the proximate analysis of coal samples typically involves the determination of Moisture Content, Volatile Matter, fixed carbon and Ash Content (Czajka, K. M., 2018)

X-ray Fluorescence (XRF): XRF analyzers were used to analyze the chemical composition of raw materials, clinker, or cement samples. They provide insights into elemental concentrations and aid in optimizing production processes (Elmrabet, R., Hmidani, Y., Mariouch, R., Elharfi, A., & Elyoubi, M. S. , 2021)

By employing these instruments during the energy audit, precise measurements were obtained, enabling a comprehensive analysis of the cement plant's energy performance and identification of potential efficiency improvements.

RETScreen software tool used in conjunction with the instruments mentioned above facilitated the collection and analysis of accurate data during the energy audit especially for electrical energy consumption of cement mills, coal mill, kiln and raw mill. This combination provided a comprehensive approach to evaluating energy performance, identifying potential energy-saving opportunities, and making informed decisions for energy efficiency improvements.

The RETScreen software tool utilized for conducting electrical energy audits in this research. The software provides a comprehensive platform for analyzing energy consumption, identifying energy-saving opportunities, and evaluating the potential impact of energy efficiency measures specific to cement plants. The electrical energy consumption and production data for the Raw mill, Cement mills, Coal mill, and kiln inputted into the RETScreen software tool and the data analyzed.

Here’s the steps followed to run the software

RETScreen software installed and launched on computer and to create a new energy analysis within the software. The data for each process (Raw mill, Cement mills, Coal mill, and kiln) was entered separately. For each process, the electrical energy consumption data was inputted, representing the energy consumed by the respective equipment or process throughout a specified year. The units of energy (kwh) and the corresponding time period (annual) were accurately specified. The production data for each process inputted to the software. This includes the relevant production volumes or quantities associated with the raw mill, Cement mills, Coal mill, and kiln for each year with units of production in ton and the corresponding time period in annual.

After analyzing the data, reports were generated within the RETScreen software to document the findings and identify potential energy savings based on the analyzed data. These reports serve as a comprehensive summary of the analysis process and provide insights into areas where energy efficiency measures can be implemented to achieve energy savings. The report includes details on energy consumption patterns, production trends, correlations between energy consumption and production.

Figure 3.1: RETScreen homepages interface (Etcheverry, J., 2021)

With this methodology, the objective is to conduct a comprehensive thermal and electrical energy audit of the National Cement share company. The analysis focuses on individual unit operations, which are examined separately and then integrated to provide a holistic view of the company's energy performance. The study utilizes energy measurements taken over a period of twelve months within the timeframe of 2022-2023. These measurements yield valuable data for conducting a thermal audit analysis. By analyzing this data, it becomes possible to gain a detailed understanding of energy usage patterns, seasonal variations, and potential areas of energy inefficiency within the facility.

By collecting energy consumption data over the course of a year, the study can capture the impact of operational changes and production level variations on energy usage. This enables the identification of trends and patterns that may affect energy efficiency, thereby facilitating a more accurate assessment of the facility's energy performance.

In order to gain a clear understanding of the subject matter, the study incorporates a review of various literature sources related to industrial energy use and efficiency in cement factories. These sources include energy audit books, case studies, previous project work, and guidelines. This review helps to enhance the researcher's knowledge and inform the analysis process.

To conduct this research, the production process of cement is thoroughly examined, including a detailed flow chart of the process, with a specific focus on the pyro-processing system and the main electrical energy-consuming equipment. The researcher studies the energy consumption of this equipment in kilowatt-hours (KWh) along with the production output, in order to gather all the necessary input-output parameters.

This paper follows a series of basic steps and procedures, as outlined below:

First Step: Preparation

Prior to conducting measurements, careful planning and preparation were carried out. The following key items were clarified:

- Selection of what needs to be measured, including the type and location of measuring or sampling points.

- Determination of the measurement duration.

- Definition of the measurement frequency, whether it's continuous recording, spot measurements, or specific time intervals.

- Checking and ensuring the accuracy of the measuring instruments and scales.

Second Step: Execution

To ensure accurate testing, it was crucial to have a stable operation of the kiln (pyro-process). Data collection took place at specific areas or points, including:

- Pre-calciner and preheater cyclones, Exhaust gas ducts (preheater and cooler), Kiln shell surface within a 2-meter gap, Surface of the cooler (top, right side, and left side), Cooled clinker leaving the cooler, Coal blower and Primary air blower.

Third Step: Methods of Calculations

Assumptions: Following assumptions are made during the test (Khalifa, S. A., & Alsadig, D. Y. ,2019)

(1) Raw materials / fuel properties, composition & feed rate are constant.

(2) The system is assumed to be in steady state condition.

(3) Kinetic & potential energy changes of input or output materials are negligible.

(4) Calculation for the heat is $Q = m*Cp*\Delta T$.

Where Q = Heat energy (kcal), m = mass of substance (Kg),

Cp = Specific heat constant, and ΔT= temperature difference.

Radiation and convection heat loss in pre-heater with calciner, kiln, tertiary air duct etc. are calculated as follows.

Radiation losses are calculated by Stefan – Boltzmann law, Radiation loss = $\sigma * \varepsilon * A * \Delta T^4$

Where, σ = Stefan – Boltzmann constant, $4.88*10^8$, ε = emissivity of metal, A = surface area (m2) and ΔT = Temp difference

Convection loss = ha*A* ΔT, where ha = convective heat transfer coefficient, A = surface area, ΔT = temperature difference (Verma, Y. K., Mazumdar, B., & Ghosh, P., 2021)

Fourth Step: Discussion

The practicality of the material and heat balance calculations is essential for the validity of the study. Therefore, the following points were taken into consideration:

- Acceptable and design (normal) values of heat consumption and gas utilization.

- Assessing the normality of heat balance and gas balance items for the given kiln system.

The last item can become quite an extensive work and the economic feasibility of West heat recovery power generation (WHRPG) considered as well.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. THERMAL ENERGY AUDIT OF PYRO-PROCESSING

A thermal energy audit of a cement plant typically involves analyzing the energy flows and thermodynamic performance of the cement manufacturing process in order to identify opportunities for energy efficiency improvements. This comprehensive assessment includes energy flows for various components including the kiln, pre-heater tower, clinker cooler, and fans. By combining data analysis, performance assessment, and thermo graphic surveys, the energy audit provides a holistic understanding of the plant's energy performance and identifies specific areas for improvement. The resulting recommendations help the plant optimize energy use, reduce energy costs, and enhance overall energy efficiency in clinker production.

The major energy use in each process step of clinker production within the boundary of the company is the combustion of fuel to generate the required heat. The company utilizes various energy sources, including electricity from grid (EEU), coal (both South African and local), and occasionally biomass. The heating values of the South African coal and local coal are 6100 kcal/kg and 4500 kcal/kg, respectively. The company's consume 60% South African coal and 40% local coal, with each type coming from different sourcing areas within the country. These proportions may vary depending on the specific requirements and availability of the coal sources. To perform a more detailed analysis of the energy use in each process step, it would be necessary to consider the specific energy requirements of the kiln, pre-heater tower, clinker cooler, fans.

To gain a comprehensive understanding of the temperature distribution, the surface temperatures of the cooler were measured four times at each distance using an infrared thermometer. This multiple measurements, any variations or patterns in the temperature distribution can be observed and analyzed. This information is valuable for assessing the efficiency of the cooling process and identifying any potential areas of concern that may require adjustments or maintenance

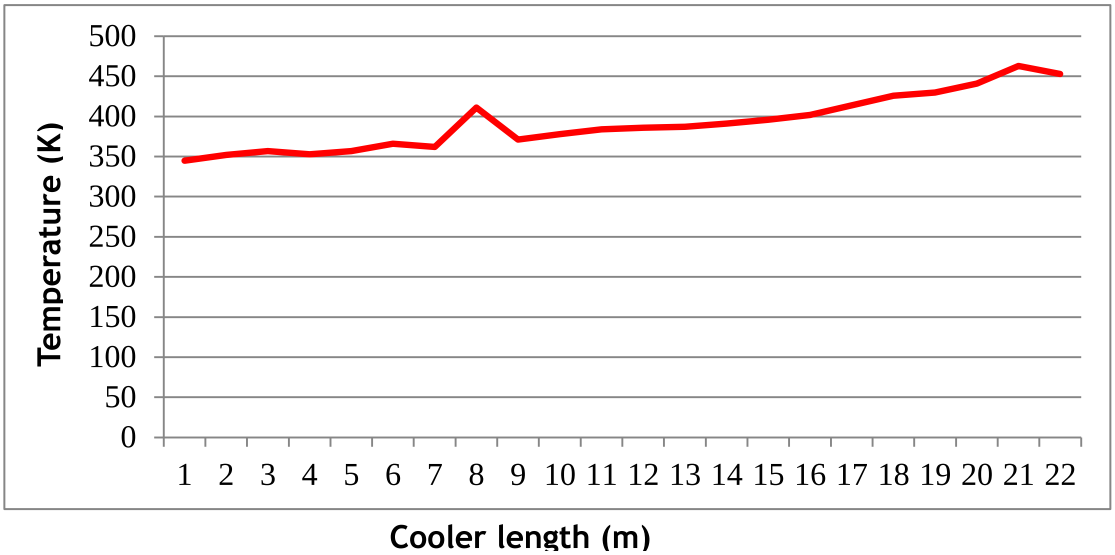

Figure 4.1: Clinker cooler surface temperature at different sections (from outlet to Inlet)

The unexpected higher values of temperature at point 8 (measuring length at 8m) in the graph compared to other points could indicate a potential issue or anomaly in that specific area of the cooler. Several factors could contribute to this observation:

Heat transfer imbalance: There might be an uneven distribution of heat transfer along the cooler's surface, leading to higher temperatures at point 8. This could be caused by variations in air flow, insulation, or other factors affecting heat transfer efficiency.

Airflow restriction: Point 8 could be experiencing airflow restrictions or reduced ventilation, preventing proper cooling in that specific area. This could be due to blockages, obstructions, or improper fan operation.

Equipment malfunction: It is also possible that there is an equipment malfunction or malfunctioning sensor at point 8, resulting in inaccurate temperature readings. This could lead to the appearance of higher temperatures at that specific location.

The kiln shell temperatures were measured using an infrared thermometer at each 2-meter interval along the entire 64-meter length of the surface. It provides a visual representation of how temperatures change from the kiln's inlet to outlet.

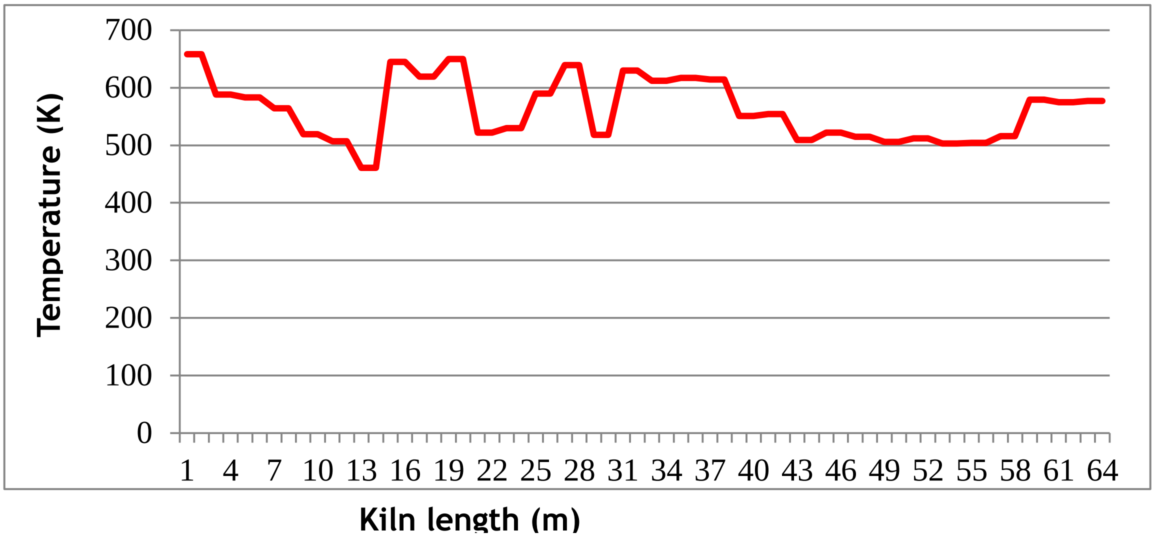

Figure 4.2: Rotary kiln surface temperature vs. Kiln length (m)

The kiln temperature profile refers to the distribution of temperatures along the length of the kiln. It provides a visual representation of how temperatures change from the kiln's inlet to its outlet.

By analyzing the kiln temperature profile, operators can identify any deviations or abnormalities in temperature distribution. This information helps in making adjustments to maintain the desired temperature range and optimize the kiln's thermal efficiency. Continuous monitoring and control of the kiln temperature profile are essential for achieving consistent and high-quality production in industries such as cement, lime, and other high-temperature processes.

The temperature profile of the kiln can be summarized as follows:

The temperature is higher at the kiln outlet compared to other points. This can be attributed to prolonged residence time, heat transfer, combustion processes, and chemical reactions occurring within the kiln.

The temperature gradually decreases from point 1 to point 14. This decrease influenced by factors such as heat loss, material cooling, and reduced heat generation as the materials progress along the kiln.

The temperature remains relatively stable from point 15- 42 or shows a slight increase in this section of the kiln. This could be due to additional heat input, such as secondary combustion (2˚air) or heat exchange with other gases or materials within the kiln.

The temperature remains uniform from 43-58 length within this section which indicates a more controlled and consistent thermal environment, possibly achieved through effective heat management and process control.

Points 58 to 64 (pre-calciner outlet): The temperature increases again towards the outlet of the precalciner. This could be due to additional fuel combustion or specific chemical reactions taking place in this region.

The specific temperature profile can vary depending on various factors, including kiln design, operating parameters, fuel type, and process conditions. Regular monitoring and analysis of the temperature profile are essential for optimizing kiln performance, ensuring product quality, and identifying any deviations that may require adjustments or corrective measures.

Figure 4.3: Rust area of cyclones exposed to high surface temperature

Heat balance on a kiln, preheater, grate cooler can offer extremely useful information on the thermal performance of the system (Madlool, Saidur et al. 2011). Heat balance show where or how the fuel heat is consumed based on the simple principle of input energy equal to output energy (*Atmaca and Yumrutaş , 2014, Engin and Ari,2005)*

The specific heat consumption of a kiln is a key parameter used to evaluate the energy efficiency of the clinker production process. The fuel consumption can be measured directly or estimated based on fuel flow rates and operating parameters. The net heat value of the fuel represents the amount of heat energy released per unit of fuel consumed and determined through laboratory analysis by using Bomb Calorimeter

By considering the various energy inputs, outputs, and heat transfers within the kiln system, a complete heat balance in determining specific heat consumption and offers a mathematical modeling approach for heat recovery from a rotary kiln. (*Söğüt, et al., 2010)* A heat balance is obviously a very efficient tool assessment of thermal efficiency (*Ramesh, et al., 2013)*

4.1.1 Material and Heat Balance

Material and heat balance calculations are often performed simultaneously as part of a comprehensive process analysis. By understanding the flow of materials and energy within a system, it's possible to identify inefficiencies, implement process improvements, and optimize resource utilization in various industries

Cooler Fan Measurement

When conducting measurement of cooler air fan flows, the following steps are typically followed

Measure cooler Fan flows ⟶ measure 1˚ air and conveying air ⟶ Calculate fuel consumption on basis of kg fuel/ kg clinker. ⟶ Finally add all input parameters

Table 4.1: Basic information's (Data's)

no	Descriptions			Value	unit
1	Kiln Dimensions	Diameter		***4.6***	M
		Length		***64***	M
2	Preheater 5 stage cyclone with ILC	Feed temperature		80	˚ C
		Raw Meal Feed rate		172	tph
		Moisture content of feed		0.8	%
		Gas after preheater		386	˚ C
		Gas Analyzer	CO_2	28	%
			CO	0.02	%
			O_2	5	%
		Dust from cyclone		10	tph
3	Firing System ; FUEL : COAL (60% on pre-calciner (50% SAC:50 % LC) and 40% of SAC on main burner)	Calorific value	SA Coal	6000	Kcal/kg
			Local Coal	4000	Kcal/kg
			Average	5000	Kcal/kg
		Temperature of coal feed		65	°C
		Kiln Primary air	temperature	55	°C
			Pitot measurement	0.073	Kg air/kg clink
		Calciner	1˚air temperature	55	˚ C
			Flow rate	0.01	Kg air/kg clink
4	Grate cooler	Exhaust Air temperature		290	˚ C
		Pitot measurement			Kg air/sec
		Clinker temperature from cooler		138	˚ C
		Cooling air Flow rate		3.188	Kg/kg clinker
		Temperature of cooling air		37	°C
5	ambient temperature /reference temperature			26.0	°C
	Pressure @ normal conditions			1.0133	Bar
	Temperature			273.15	˚ K
	Number of molecules			$6.02*10^{26}$	Molecule/mol.

Coal was the primary fuel used for both the calciner and main burners during the measurements. In some cases, a small amount of biomass was also used. The specific data for coal was gathered using proximate analysis or thermo gravimetric analysis (TGA) and compiled in NCSC laboratory.

Thermo gravimetric analysis (TGA) is a technique used to analyze the thermal behavior and composition of a substance as it undergoes heating or cooling. TGA is commonly employed to determine the proximate analysis of coal, which includes the determination of various parameters such as moisture content, volatile matter, fixed carbon, and ash content. During TGA, the coal sample conducted in a controlled atmosphere to prevent oxidation or combustion environment under specific conditions. In the temperature range of 30°C to 950°C in N_2 atmosphere (99.99% pure) at a constant flow rate of 40 mL/min (Dwivedi, K. K., Karmakar, M. K., & Chatterjee, P. K., 2020)

Moisture content is an important parameter in coal analysis. It is needed for determining the calorific (heating) value and handling properties of a coal. The moisture value given for a proximate analysis is the moisture measured as mass lost from a sample under specified conditions after heating in a moisture oven to 105 to 110°C (ASTM method D3173-11); This is the moisture value used for calculating other analytical results to a dry basis. It can be used in conjunction with air-dried moisture to calculate on an as-received basis

The factory sourced both South African coal and local coal to feed the kiln burner and calciner burner, using different ratios. The kiln/main burner receives a minor fraction, representing 40% of the total heat input. On the other hand, the calciner enjoys a significant portion, amounting to almost two-thirds of the total heat input. This suggests that the calciner burner receives a larger share of the coal fuel, while the kiln/main burner receives a smaller portion.

The specific ratios and proportions of South African coal and local coal used in the kiln burner and calciner burner would depend on the specific requirements and optimization strategies of the factory. These ratios may be adjusted based on factors such as coal quality, availability, cost, and combustion characteristics.

The compositions of the fuel, kiln feed, and clinker were determined using standard procedures; the results presented in Tables 4.2 & 4.3,4.5 and 4.6 respectively. Average value of each set of data is used throughout the study. In order to represent normal operating conditions for a stabilized operation

Common parameters of Coal/Basis:

<u>As-received moisture (ar)</u>: Moisture (water) in a sample upon delivery to a lab.The same as as-delivered moisture. Also used as a recording standard (denoted as "ar" or "AR"). As-received (AR) moisture equals air-dried loss moisture plus residual moisture (measured from the proximate analyzer).

<u>Air-dried moisture (ad)</u>: Moisture (water) in a sample after air-drying. Air-drying removes surface moisture prior to analysis. Because this term was also sometimes used for residual moisture**,** it was withdrawn by the American Society for Testing and Materials (ASTM method D121-09). The air-dried recording standard (denoted as "ad" or "AD") remains valid for inherent moisture.

Moisture (Mad)

About 1 g of finely powered air-dried coal sample is weighed in a crucible. The crucible is placed inside an electric hot air-oven, maintained at 105° - 110°C. The crucible is allowed to remain in oven for 1 hour and then taken out, cooled in a desiccator and weighed. Loss in weight is reported as moisture (on percentage basis).

Percentage of moisture = (Loss in weight) / (wt. of coal taken) x 100

Volatile Matter (Vad)

The dried sample of coal left in the crucible after moisture analysis is then covered with a lid and placed in an electric furnace (muffle furnace), maintained at 925°± 20°C. The crucible is taken out of the oven after 7 minutes of heating. The crucible is cooled first in air, then inside a desiccator and weighed again. Loss in weight is reported as volatile matter on percentage-basis.

Ash (Aad)

The residual coal in the crucible after analysis of volatile matter is then heated without lid in a muffle furnace at 700 ± 50°C for 1/2 hour. The crucible is then taken out, cooled first in air, then in desiccator and weighed. Heating, cooling and weighing is repeated, till a constant weight is obtained. The residue is reported ash on percentage-basis.

Fixed carbon (FCad)

Percentage of fixed carbon= 100 - % of (moisture + volatile matter +ash)

The factory sourced both South African coal and local coal to feed the kiln burner and calciner burner, using different ratios. The kiln/main burner receives a minor fraction, representing 40% of the total heat input. On the other hand, the calciner enjoys a significant portion, amounting to almost two-thirds of the total heat input. This suggests that the calciner burner receives a larger share of the coal fuel, while the kiln/main burner receives a smaller portion.

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Table 4.2: Coal consumption and analysis data (Ave) as per NCSC quality control manual

Firing point	**SiO_2**	**CaO**	**MgO**	**Fe_2O_3**	**Al_2O_3**	**SO_3**	**MC**	**Heat value**	**Consumption**	**remark**
	(%)	(%)	(%)	(%)	(%)	(%)	%	CV(kcal/kg)	(Kg/hr.)	
Kiln/Main burner	50.56	7.01	2.22	2.39	29.35	-	2.57	6014	7300	40% of SAC (100%)
Caciner	47.94	6.45	2.44	2.19	31.12	-	2.57	4541	1400	60% of (50 SA +50%LC)
Total Coal consumption (kg/hr)									21300	

Table 4.3: Coal proximate analysis test results

Coal Sourcing	Sample wt.(gm.)	Mar (%)	Vad (%)	FCad (%)	Mad (%)	Aad (%)	Heat value /CV (kcal/kg)	Remark
South Africa	1.0088	8.6	42.81	41.85	4.26	11.08	6053	Beneficiated
Ethiopia (Local coal)	1.0091	14.65	37.52	30.43	2.16	30.55	4657	Unbeneficiated

Table 4.4: Raw meal chemical composition laboratory test results (XRF data)

Compositions	CaO(%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	LOI(%)	MgO(%)	SO_3 (%)	SUM
RM achieved	43.86	13.25	2.94	2.16	35.33	0.94	0.15	98.63

Table 4.5: Kiln feed chemical composition laboratory test result (XRF data)

Compositions	CaO (%)	LOI (%)	KH (%)	SM (%)	AM (%)	LSF(%)	Moisture(%)
RM achieved	43	36.5	1.41	2.19	2.18	1.4	0.8

Table 4.6: Clinker chemical composition test result

	CaO	SiO_2	Al_2O_3	Fe_2O_3	LOI	MgO	SO_3	SUM	F-CaO
%	65.27	21.55	5.39	3.59	0.45	1.68	0.5	98.43	1.61
	Calculated phase compositions (%)						C_4AF	C_3S	C_2S
							8.4	54.04	21.32

C_2S, C_3S, C_4AF, and C_3A are chemical compounds commonly found in Portland cement (clinker), which is a key ingredient in concrete production. These compounds contribute to the properties and behavior of the cement during hydration and setting processes.

C_2S (Dicalcium Silicate or Belite): C_2S is one of the primary constituents of Portland cement; it reacts with water during cement hydration, contributing to the development of strength over time. It hydrates relatively slowly and provides long-term strength to the hardened concrete.

C_3S (Tricalcium Silicate or Alite): is the main compound in Portland cement, constituting; It is responsible for the initial setting and early strength development of the cement. C3S hydrates rapidly, releasing a significant amount of heat during the early stages of hydration, which is important for early strength gain in concrete.

C_4AF (Tetracalcium Alumino Ferrite): is a minor component of Portland cement; it contributes to the color of cement, with higher amounts of C4AF resulting in darker cement. During hydration, C4AF hydrates more slowly compared to C3S and C2S, and its contribution to the strength of concrete is relatively limited.

C_3A (Tricalcium Aluminate): is another minor component of Portland cement, comprising and it plays a crucial role in the early setting of cement. C3A reacts rapidly with water, leading to the initial formation of ettringite, a calcium aluminum sulfate compound.

Gas analyzers are commonly used at the kiln inlet and cyclone outlet in cement industries to monitor and analyze the composition of gases at these specific points. The gases analyzed at these locations provide valuable insights into the combustion efficiency, emissions, and overall process performance (Hussnain, S. A., Farooq, M., Amjad, M., Riaz, F., Tahir, Z. U. R., Sultan, M., ... & Bokhari, A., 2021). Gas analyzers are installed at kiln inlet and cyclone-1 outlet

Oxygen (O_2): are commonly installed at the kiln inlet and cyclone outlet to measure the oxygen concentration in the gases. Monitoring oxygen levels helps assess the combustion efficiency and air-to-fuel ratio. It enables adjustments to optimize fuel usage, reduce fuel consumption, and minimize emissions.

Carbon Monoxide (CO) Analyzer: CO levels can indicate incomplete combustion or other combustion-related issues. Monitoring CO levels helps optimize the combustion process, ensure proper fuel-air mixing, and minimize CO emissions.

Table 4.7: Gas analyzer results (from NCSC CCR data)

	Kiln inlet	Cyclone 1 outlet
O_2	5	4
CO	0.01	0.02

4.1.1.1. Gas balance

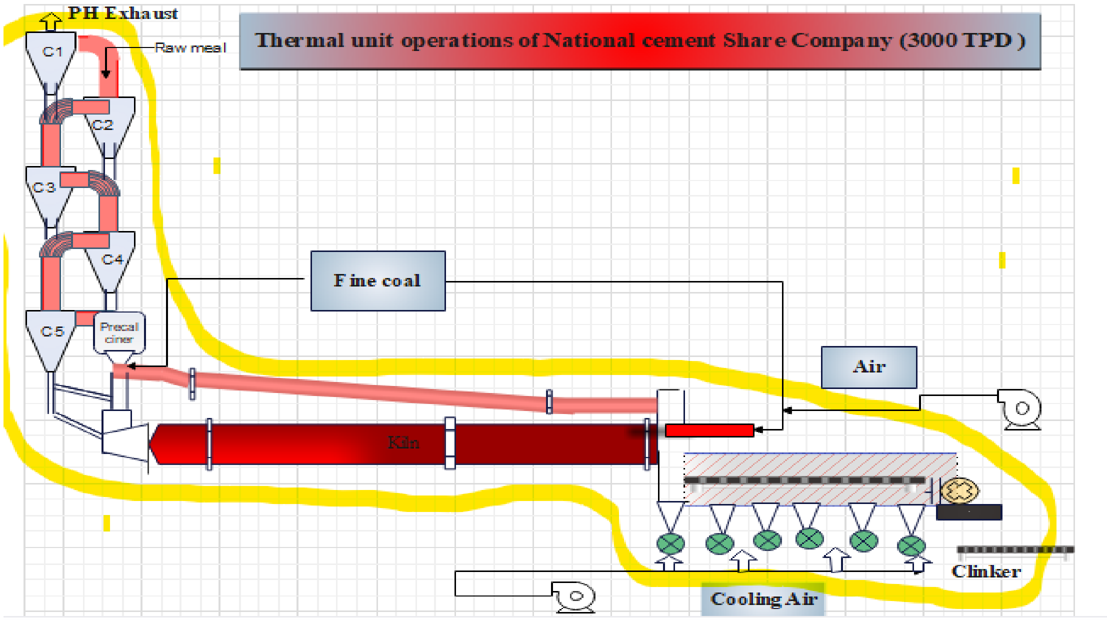

Figure 4.4: Controlled volume of heat and material balance which is dust is inside circulation

i. Gases entering to the system

When considering the gas entering the clinker cooler in a cement plant, it typically refers to the exhaust gases from the kiln system. These gases, which contain heat and various pollutants, are directed into the clinker cooler for the purpose of cooling the clinker and recovering waste heat. The specific characteristics of the gas entering the clinker cooler can vary depending on factors such as the type of kiln system, fuel used, and operating conditions.

To cool down clinker in a clinker cooler system, the air flow rate needs to be calculated based on the desired cooling efficiency and the specific requirements of the process

To find the air volumetric flow rate (m^3/hr.) for a clinker cooler;

Air Volumetric Flow Rate = Air Velocity (m/s) * Cross-sectional Area of effective diameter (m^2)

Cooler air volume flow rate = velocity of air * cross sectional area of effective diameter

Air pressure above sea level can be calculated as

$P = 101325 (1 - 2.25577*10^{-5} h)^{5.25588}$ (Kutz, M. (Ed.). (2006))………… …………………… (4.1)

Pressure at sea level (pa) = 101325 at normal temperature and pressure

p = air pressure (Pa)

h = altitude above sea level (m); NCSC altitude = 1146m

The air pressure at altitude 1146 m can be calculated as;

$p = 101325 (1 - 2.25577\ 10^{-5} * (1146\ m))^{5.25588} = 88.3 KPa$

Conversion of actual condition to normal condition

Volume Vn= V*P*Tn/ (T*Pn) ; Density ρ = ρn*P*Tn /(T*Pn)

Moisture of air = volume of water in air / volume of air = Vx/Vtot = Px/Ptot

Px = humidity of air * saturated vapor pressure

Humidity of air = 60% ; Saturated vapor pressure = 4200 Pa ;Normal pressure = 101330 Pa, Normal temperature = 273K

Overall Mass Balance

Step1

Measure cooler Fan flows

Then, measure primary air and conveying air

Calculate fuel consumption on basis of kg fuel per kg clinker.

Important thing to keep in mind the kiln should be in stable condition

Finally add all input parameters

Cooler Fan flow = kg air/kg clinker…………………………………...1

Primary Fan Flow = kg air/kg clinker……………….………………...2

Conveying air Flow = kg air/kg clinker……………….……………….3

Fuel = kg fuel/kg clinker…………………………….……………....4

Kiln feed = kg /kg clinker…………………..………………………. 5

Input moisture = kg/kg clinker………………………………………6

Input = 1+2+3+4+5+6

* 10 *3600 = 23,040 m^3 /hr.

Convert into Kg/hr. = 23,040m^3/hr. x 1.21kg/m^3 (corrected density) = 27,878.40 Kg air/hr.

Kg air/kg clinker = 27,878.40 Kg air/hr. / (110 ton/hr. X 1000Kg/1ton) = 0.25 kg air/ kg clinker

Nm3/kg Clinker = 0.25Kg air/kg clinker / (1.29 Kg/Nm^3; density of air) = 0.20 Nm3 /kg clinker

Cooler FN10

Q (m3 /hr.) = A X Average Velocity = 1.63 X 9.75x3600 = 57,213 m^3 /hr.

Convert into Kg/hr. = 57,213m^3/hr. x 1.21kg/m^3 (corrected density) = 69,227.73 Kg air/hr.

Kg air/kg clinker = 69,227.73 Kg air/hr. / (110 ton/hr. X 1000Kg/1ton) = 0.63 kg air/ kg clinker

Nm3/kg Clinker = 0.63Kg air/kg clinker / (1.29 Kg/Nm^3; density of air) = 0.49 Nm3 /kg clinker

Cooler FN11

Q (m3 /hr.) = A X Average Velocity = 0.08 X 18.15x3600 = 5227.2 m^3 /hr.

Convert into Kg/hr. = 5227.2m^3/hr. x 1.08kg/m^3 (corrected density) = 5645.38 Kg air/hr.

Kg air/kg clinker = 5645.38 Kg air/hr. / (110 ton/hr. X 1000Kg/1ton) = 0.05 kg air/ kg clinker

Nm3/kg Clinker = 0.05Kg air/kg clinker / (1.29 Kg/Nm^3; density of air) = 0.04 Nm3 /kg clin

Similarly, the remaining cooler fans also calculated and its value displayed in the table

Table 4.8: Cooler fan flow measurement results

Cooler NO.	Average Velocity (m/s)	area of screening (m^2)	Q = V *Area (m^3/hr.)	Density of air @ambient temp.	Kg air/hr.	Kg Air/Kg clinker	Nm^3/Kg clinker
FN9	10	0.64	23040	1.21	27878.4	0.25	0.2
FN10	9.75	1.63	57213	1.21	69227.73	0.63	0.49
FN11	18.15	0.08	5227.2	1.08	5645.38	0.05	0.04
FN12	32.28	0.08	9296.64	1.01	9389.61	0.09	0.07
FN13	8.34	0.21	6305.04	1.1	6935.54	0.06	0.05
FN14	7.39	0.14	3724.56	1.09	4059.77	0.04	0.03
FN15	19.26	0.08	5546.88	1.09	6046.1	0.05	0.04
FN16	13.82	0.08	3980.16	1.03	4099.56	0.04	0.03
FN17	12.81	0.11	5072.76	1.22	6188.77	0.06	0.04
FN18	11.22	0.11	4443.12	1.07	4754.14	0.04	0.03
FN19	6.33	0.85	19369.8	0.98	18982.4	0.17	0.13
FN20	18.28	0.53	34878.24	1	34878.24	0.32	0.25
FN21	7.26	0.51	13329.36	0.97	12929.48	0.12	0.09
FN22	3.22	0.79	9157.68	0.97	8882.95	0.08	0.06
Raw meal feed = 172 TPH RM:CL Factor = 1.56 Clinker output = 110 TPH			200,584.40	SUM	219,898.07	2	1.55

Total cooler fan air inputs = **181935 Nm^3/hr.**

Corrected density considers the actual conditions under which the measurement is made, while standard density represents the density under specific standard conditions.

$Nm^3/hr = (m^3/hr * T\_std) / T\_actual * (P\_actual / P\_std)$

To calculate the corrected density of air, it needs to account for variations in temperature, pressure, and humidity. The corrected density of air takes into consideration these factors to provide a more accurate representation of the air density under specific conditions

The specific cooling air requirement for the clinker cooler in this system is lower than the typical 1.55 Nm^3/hr. instead of 1.65 to 2.5 Nm3/kg clinker (International Cement Review, 2018). A lower specific cooling air requirement indicates more efficient cooling, as it means that less air is needed to achieve the desired cooling effect per unit of clinker. However, the output of clinker in the system is high. In such a scenario, it is recommended to increase the cooling air to the system. This is because a higher clinker output means that more heat is being generated, and thus, more cooling air is required to effectively dissipate that heat and maintain the desired cooling temperature.

Volume of primary air entering to the system:

The calciner primary air and kiln primary air which enters to the fuel pipe is determined by the pressure. The primary air is entered through a pilot tube to both two burners with a diameter of 0.38m. Taking the ambient air at 26˚C temperature having a density to be ρ = 1.22 kg/m^3. Therefore, the above parameters can be calculated by the following mode of air velocity formula and velocity pressure is 130 mbar:

$v = Kp \times \sqrt{2 * \Delta P/\rho}$ .... (4.2)

(Laursen, A. L., Moody, F. J., & Law, J. C. (2005, January)

KP = Apparatus $constant$(S-type pitot tube) = 0.84

ΔP = Differential pressure between total pressure and static pressure; = 130 pa (130 kg/ms^2) (dynamic pressure)

$\rho = density\ of\ air$ = 1.2 Kg/m^3

$v = 0.84 \times \sqrt{2 * 130/(1.22})$ = 12.26 m/s

Area of the pipe, A = π ×D^2/4

= 3.14*(0.38^2/4) = 0.113354 m^2

The amount of air entered through the pipe (volume flow rate) and the mass flow rate can be calculated using eq. 4.3 and 4.4

Q = $A \times v$ = 0.113354 m^2 × 12.26 m/s *3600sec/hr.) = <u>5004.1 m^3/hr.</u> (4538.83Nm^3/hr.) . …. (4.3)

$m = \rho \times V$ = 1.22 kg/m^3 × 5004.1 m^3/hr. = <u>6105 kg/hr</u>. … … … … … ….… ………………. (4.4)

This value assumed to be the same to both the kiln primary air and calciner primary air

Kg air /Kg clinker = 6105 kg/hr. /(110 ton/hr. *1000 kg clinker /1ton) <u>= 0.0555 kg air/kg clinker</u>

Nm^3/ kg clinker = 0.0555 kg air/kg clinker /1.29 kg air /Nm^3 = **<u>0.043 Nm^3/kg clinker</u>**

The volume of the blower below calculated from design value

Kiln outlet coal blower = 4440.0 m^3/hr. 4027.2 Nm^3/hr.

PC coal blower = 3960.0 m3/h, 3592 Nm^3/hr.

PC fuel air = 3770.0 m3/h. 3419.5 Nm^3/hr.

ii. Gas produced in the system

Gas from coal burning

To achieve efficient combustion in a cement kiln flame three things are necessary; sufficient combustion air supply, primary air momentum, and proper fuel atomization.

- Sufficient combustion air supply: Adequate air supply is essential for the combustion process. This primary air is typically introduced through a burner pipe along the fuel which provides a portion of the combustion air required for the fuel combustion
- Primary air momentum: The primary air is supplied with a certain momentum to ensure proper mixing and dispersion of the fuel particles in the kiln. This helps in achieving good fuel-air mixing and promoting efficient combustion.
- Proper fuel atomization: to breaking down the fuel into small droplets or particles to facilitate better mixing with the air.

Additionally, to optimize combustion efficiency, preheated secondary air is introduced through a vent located near the cooler. The preheating of the secondary air helps in improving the combustion process by increasing the temperature and enhancing the reaction kinetics. Combustion of fuels is a chemical reaction of fuel with oxygen (O_2) according to the general scheme:

(Otto Labahn, 1983) Fuel + Oxygen → combustion productions (CO_2, H_2O, SO_2, Ash)

$$C + O_2 \rightarrow CO_2 \text{ (1kmol C +1 kmole } O_2 = \text{1kmol } CO_2\text{)}$$

1 mole of carbon reacts with 1 mole of oxygen to produce 1 mole of carbon dioxide.

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \text{ (2kg } H_2 + \text{16 kg } O_2 = \text{18kg } H_2O\text{)}$$

Here, 1 mole of hydrogen reacts with 1/2 mole of oxygen to produce 1 mole of water.

$$S + O_2 \rightarrow S_2O \text{ (32kg S + 32kg } O_2 = \text{64 kg } SO_2\text{)}$$

Hence: the complete combustion of S kg of Sulphur requires S kg of Oxygen. Taking account of the oxygen already contained in the coal, the quantity of oxygen required for the complete combustion of 1kg of coal is theoretically

2.67 C + 8 H – O + S (kg)………………………………………………………………… (4.5)

The complete reaction of the carbon component of the fuel with oxygen results in the production of carbon dioxide (CO_2) and the release of the full calorific potential of the fuel. This complete combustion is desirable for efficient and clean combustion, as it minimizes the formation of incompletecombustion byproducts such as carbon monoxide (CO) or unburned hydrocarbons.

Avoiding the formation of CO in the flame is particularly important when sulphates are present in the kiln, as sulphates decompose liberating gaseous SO_2 in the presence of CO.

$$SO_3 + CO \rightarrow SO_2 \uparrow + CO_2 \uparrow$$

- **Air requirement**

1kg of air contains 0.23kg of oxygen and 0.77kg of nitrogen.

For the standard conditions: 1 m^3 of air = 1.293 kg of air, Hence 1m^3 of air = 0.21 m^3 of oxygen + 0.79 m^3 of nitrogen.

Hence the air requirement per kg of coal is

W_T = 11.6 C + 34.78 H + 4.35 S – 4.35 O (kg / kg)……………………………….…….. (4.6)

(Otto Labahn, 1983) The air requirement in Nm^3 (M^3 under standard conditions) per kg of coal is

$W_V = W_T / 1.293$ ………………………………………………………………………… (4.7)

However, theoretical or stoichiometric air is insufficient for complete combustion **EXCESS AIR** (stoichiometric & air & excess air) is needed for complete combustion.

Oxygen for combustion of fuels is taken from air. For the considerations within this paper the composition of the dry air can be simplified (neglecting trace gases) as follows:

Oxygen (O_2) = 23.0 Vol% and Nitrogen =79.0Vol% .Air =100 %

Minimum Air and Air factors

To perform a complete combustion a theoretical minimum amount of oxygen (O_2 min) is required, the corresponding minimum quantity of air is Amin :

Amin = O2 min / 0.21 ………………………………………………………………… (4.8)

Where:

Amin is the minimum quantity of air required for complete combustion, measured in normal cubic meters (Nm^3).

O_2 min is the theoretical minimum amount of oxygen required for complete combustion, typically expressed as a fraction or percentage.

In this formula, 0.21 represents the approximate percentage of oxygen in atmospheric air (21%). This assumes that air consists of approximately 21% oxygen and 79% nitrogen.

It's important to note that this calculation provides estimation based on ideal stoichiometry and assumes complete combustion without any excess air. In practical applications, additional air is often supplied to ensure complete combustion and account for variations in fuel composition and other factors

$n = A/A_{Min}$ ……………………………………………………………….(4.9)

A is the effective air quantity, n must be always higher than 1 in order to maintain complete combustion (Cement Seminar).

- **Combustion calculations**

To demonstrate the calculations method, the simple example of combustion of pure carbon is given as example. The combustion of 1 kg of pure carbon (C) without any excess air (n=1) is considered.

The combustion equation and the corresponding weights and volumes are as follows (Paraschiv, L. S., Serban, A., & Paraschiv, S., 2020).

$$C + O_2 \rightarrow CO_2$$

The above equation refers to 1 kmol or 12 kg of C. The final results are wanted per 1 kg of C i.e. per 1 kg of fuel.

The minimum oxygen is : $O_2min = 22.4\ Nm^3/12\ kg = 1.87\ Nm^3/kg\ C$

Air contains 23 % O_2.therefore

$A_{min} = 1.87 / 0.21Nm^3/kg\ C = 8.9\ Nm^3 / kg\ C$

The combustion products are only CO_2 and N_2 (coming from A_{min}) :

$CO_2 = 22.4\ Nm^3/12\ kg = 1.87\ Nm^3/kg\ C$

$N_2 = A_{min} *0.79 = 7.035\ Nm^3/kg\ C$

Total combustion gas = $V_{min} = 8.905\ Nm^3/kg\ C$

In general a fuel is given either by its elemental composition or by its volume composition in case of gases. Therefore two types of formula are required (A and B) which are based either on weight composition or on volume composition of the fuel.

A_{min} = Minimum air , V = Minimum composition gas

Calculation based on elemental analysis /weight composition

C, H, S, N, O, H_2O are the weight fraction (kg/kg fuel) of carbon, hydrogen, sulfur, nitrogen, oxygen and water in the fuel.

$A_{min} = 8.89 * C + 26.5 * H + 3.3*S – 3.3*O\ (Nm^3/kg\ fuel)$……………………………….(5.0)

Table 4.9: Coal elemental compositions by chemical analysis method

C(Carbon)	H(hydrogen)	O(oxygen)	N_2(Nitrogen)	S(sulfur)	H_2O	Ash
64%	5%	5%	2.50%	1.50%	2.5% ,	19%

Consumed Air

$A_{min} = 8.9 *C + 26.5*H + 3.3*S – 3.3*O\ [Nm^3/kg\ fuel]$

$A_{Min} = 8.9*0.64+26.5*0.05+3.3*0.015 – 3.3*0.05 =$ **$7.236Nm^3/kg$ fuel**

Produced gas

V_{min} = 0.79 * A_{min} + 0.8 * N + 1.87*C +0.7*S+11.2*H+1.24*H_2O+A_{min} *H_2O_{air} [Nm^3/kg fuel]

V_{Min} = = 0.79 * 7.236 + 0.8 * 0.025 + 1.87*0.64 +0.7*0.015+11.2*0.05+1.24*0.025+7.23*0

= 7.535 Nm^3/kg fuel

Excess air

At Kiln Inlet

- A certain excess air is maintained in the kiln inlet to avoid CO formation and reducing conditions in kiln
- Increase in kiln draft increases the heat consumption but neutralized by the increased heat recuperation from the cooler

The amount of excess air during operation is determined by the Oxygen content in the kiln inlet and preheater exit, which continuously monitored by the on-line gas analysers.

= (% oxygen at kiln inlet *produced air) / (0.21*(1-%oxygen at kiln inlet)

= (0.05*7.535)/ (0.21-0.05) = 2.35 Nm3/kg coal

= (%oxygen at kiln inlet *79)/ (0.21*(100 - % CO2 combustion) - %oxygen at kiln inlet

$$\% \text{ Excess Air} = \frac{\%O_2 \text{ at kiln inlet} * 79}{0.21 * (100 - \% \text{ CO2 combustion}) - \%O_2 \text{ at kiln inlet}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

= (5*79) / (0.21*(100-4) - 5) = 26 %

At C1 preheater outlet

= (%oxygen at kiln inlet *produced air)/ (0.21*(1-%oxygen at kiln inlet)

= (0.05*7.535)/ (0.21-0.05) = 2.35 Nm3/kg coal

Excess air percentage = (%oxygen at preheater outlet *79)/ (0.21*(100-%CO2 combustion) - %oxygen at preheater outlet

= (3.5*79)/ (0.21*(100-11)- 3.5) = 18.2%

Gas produced in the system = (7.535 + 2.35)*21300 kg/hr. = **210,550.5 Nm3/hr.**

- **Gas from raw material LOI**

= kiln feed * LOI% / (0.9*44+0.1*18); 10% H_2O and 90 % of CO_2

$$= \frac{172{,}000 * (36.5 \text{ kiln feed} - 0.45 \text{ clinker}) / 100}{(0.9*44+0.1*18)} * 22.4 = \mathbf{33{,}549 Nm^3/hr.}$$

i. Gases out from the system

For large pressure orifices in high dust environment like cement industry stack (ISO, 10780) S-type pitot tubes are used

- **Volumetric flow rate of C1 preheater outlet gas**

The calciner primary air and kiln primary air which enters to the fuel pipe is determined by the pressure. The outlet diameter of C1 is 3m. Taking the cyclone one outlet temperature at 386 ˚C temperature having a density to be ρ = 0.4486 kg/m^3. Therefore, the above parameters can be calculated by the following mode of air velocity formula and velocity pressure is 157.08 pa:

$v = Kp \times \sqrt{(2*\Delta P/\rho)}$ ……………………………………………………………………(5.2)

(Laursen, A. L., Moody, F. J., & Law, J. C., 2005)

KP = Apparatus $constant$ (S-type pitot tube) = 0.84

ΔP = Differential pressure between total pressure and static pressure; = 157.083 pa

(157.083 kg/ms2) (Dynamic pressure)

$\rho = density\ of\ air$ = 0.44864 Kg/m3

$v = 0.84 \times \sqrt{(2*157.083/(0.4486))}$ = 22.23 m/s

Area of the pipe, A = $\pi \times D^2/4$ **= 3.14*(3^2/4) = 7.065 m^2**

The amount of air leaves through the pipe (volume flow rate) and the mass flow rate can be calculated as ; Q = $A \times v$ = 7.065 m^2 × 22.23 m/s *3600sec/hr.) = 565,397.82 m^3/hr. or **226068 Nm^3/hr**.

$m = \rho \times V$ = 0.4486 kg/m^3 × 565397.82 m^3/hr. = 253,637.5 kg/hr.

Kg air /Kg clinker = 253,637.5 kg/hr. /(110 ton/hr *1000 kg clinker /1ton) = 2.306 kg air/kg clinker

Nm^3/ kg clinker = 2.306 kg air/kg clinker /1.29 kg air /Nm^3 = **1.787 Nm^3/kg clinker**

Volumetric flow rate of cooler exhaust gas: The cooler exhaust duct or chimney diameter of 2.8 m with temperature outlet of 290˚C temperature having a density to be ρ = 0.48126 kg/m^3. Therefore, the above parameters can be calculated by the following mode of air velocity formula and velocity pressure is 91.67 pa:

$v = Kp \times \sqrt{(2*\Delta P/\rho)}$ ……………………………………………………………………….. (5.2)

KP = Apparatus $constant$ (S-type pitot tube) = 0.84

ΔP = Differential pressure between total pressure and static pressure; = 91.67 pa

(91.67 kg/ms2) (Dynamic pressure), ρ = $density\ of\ air$ = 0.48126 Kg/m3

$v = 0.84 \times \sqrt{(2*91.67/(0.48126))}$ = 16.395 m/s

Area of the pipe, A = $\pi \times D^2/4$ = 3.14*(2.8^2/ 4) = **6.1544 m^2**

Q = $A \times v$ = 6.1544 m^2 × 16.395 m/s *3600sec/hr.) = 363,245 m^3/hr. or **159224 Nm^3/hr.**

$m = \rho \times V$ = 0.48126 kg/m^3 × 363,245 m^3/hr. = 174,815.2887 kg/hr.

Kg air /Kg clinker = 174,815.2887 kg/hr. / (110 ton/hr. *1000 kg clinker /1ton) = 1.5892 kg air /kg clinker

Nm^3/ kg clinker = 1.5892 kg air/kg clinker /1.29 kg air /Nm^3 = **1.232 Nm^3/kg clinker**

- **Gas consumed by the system**

Gas consumed by the system = 7.236 Nm^3/ kg coal * 21300 kg coal /hr. = **154,126.8 Nm3/hr.**

Normal volume of blaster and false air = air out - air in

Air out put = 226068 Nm3/hr. + 159224 Nm3/hr. + 154126.8Nm3/hr. = **539418.8 Nm3/h**

Air in put = 181935 Nm^3/hr. + 4538.8 Nm^3/hr. + 4027.2 Nm^3/hr. + 3592 Nm^3/hr. + 3419.5 Nm^3/hr. + 210550.5 Nm^3/hr. + 33549 Nm^3/hr. = **441612 Nm^3/hr.**

False air = 539418.8 Nm^3/hr. – 441612 Nm^3/hr. = **97806.8 Nm^3/hr.**

Table 4.10: Summarized Gas Balance

	Normal condition (Nm^3/h)	Actual condition (m^3/h)	relative to clinker produced (Nm^3/kg clinker	%
Gas Input				
primary air	4539	5004.1	0.043	1.7
Cooler air	181935	200,584.4	1.55	60
False air	97806.8	107110	0.89	34.4
Kiln outlet coal blower	4027	4440	0.037	1.4
Pc coal blower	3592	3960	0.032	1.2
Pc fuel air	3419.5	3770	0.031	1.2
Total gas input	**295319**	324868.5	2.583	
Gas produced				
Gas from coal burning	**210551**	231606	1.91	86.
Gas from LOI	**33549**	36904	0.305	14
Out put				
C1 outlet gas	226068	565397.8	1.787	59
Cooler exhaust gas	159224	363245	1.232	41
Total gas output	**385292**	928643	3.019	100
Gas used				
Gas used by coal	**154127**	169540	1.401	

Input air + generation air = output air + consumption air

295319 M^3/hr. + 244100 M^3/hr. = 385292 M^3/hr. + 154127 M^3/hr. ; 539419 M^3/hr. = 539419 M^3/hr.

4.1.1.2. Solid material balance

Material input

The mass balance has been made on the pyro processing system for which the boundary of the system is defined as shown on fig4.5 the streams of data were obtained from actual operating data of the plant. The rate of flow of kiln feed, dust in exhaust, coal ash and loss on ignition (LOI) was used to obtain ratio of kiln feed to clinker ratio. The loss of feed as exhaust gas from calcination and dehydration of raw material is known to be loss on ignition (LOI)

In the burning process, volatile constituents are driven out of the raw materials. More particularly, carbon dioxide (CO_2) is driven out of the limestone and water of hydration is driven out of the clay. As a result, the materials undergo a decrease in weight in the production of cement clinker.

The carbon dioxide is driven out of the limestone:

CaCO3 = CaO + CO_2

100 parts CaCO3 = 56 parts CaO + 44 parts CO_2

Laboratory test result of raw meal shows 77 %$CaCO_3$, which gives 64.5% of clinker, for an ignition loss of 35.5% (or: 1kg of raw meal yields about 0.645kg of clinker)

For different values of the $CaCO_3$ of the raw meal the quantities of materials can be calculated with the following formulas:

1-[(0.44*%$CaCO_3$)/100 + 0.07 * (100 - %$CaCO_3$)/100)](kg clinker/kg raw meal)………..................... (5.3)

= 1-[(0.44*77%)/100 + 0.07*(100 – 77%)/100] = 0.645 kg clinker/kg of raw meal

1/a = 1kg of raw meal / 0.649 kg clinker = 1.55 kg raw meal/kg clinker

% $CaCO_3$ * 56/a*100 = % CaO in clinker

= (76% *56)/0.649*100 = 65.6 % CaO in clinker

Taking account of losses of materials in the manufacturing process, it is generally assumed in practice that 1.5 – 1.60 kg of raw material is needed for producing 1kg of clinker

Determination of clinker production can be made by direct weighing of the production which is by far the best method. But in some cases no direct measurement is possible. Therefore, an indirect determination may be necessary. The best method in such a case is to establish a mass balance for the system. Similar to a heat balance a boundary for a mass balance can be defined

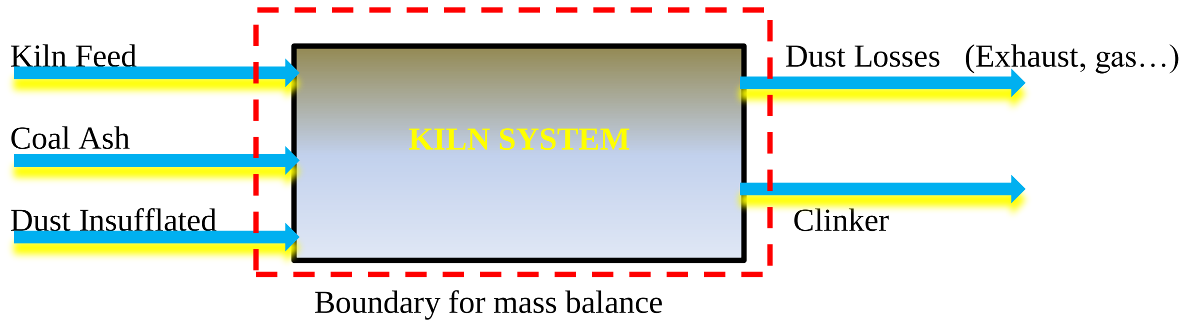

Figure 4.5: Mass balance on the kiln system

Clinker = (kiln feed + coal ash + dust insufflated – dust losses) all calculated on LOI free basis

The following additional remarks can be given:

- The boundary for the mass balance does not necessarily have to coincide with the heat balance boundary.
- The mass balance boundary must cut the kiln feed measuring point (because the mass flow is known at this point).
- The balance is always made on a loss-on-ignition-free (L.O.L.-free) base (no balance for the entire quantity including L.O.L. can be made since part of it is converted to gas, which is not included here)

Regarding only the dust loss from the exhaust gas there are two basic possibilities: Dust Flow crosses mass balance boundary and does not leave mass balance boundary (internal dust return)

Table 4.11: Mass balance on the Kiln

	M_f (dry) [t/h]	LOI. [-]	M_f (1-LOI) [t/h]
Kiln feed (KF)	172	0.365	109.22
Coal Ash (Ash)	3.723	~ 0	3.723
Dust in Exhaust (D)	10.32	0.32	-7.0176
Dust insufflated (3.75%)		~ 0	4.09575
Clinker (cli)		~ 0	110.09

Note that the kiln feed data (LOI.) may slightly change when going from combined operation to direct operation or vice versa!

Kiln Feed / Clinker = R = 172 / 110.09 = 1.56

The dust insufflation of the plant to modify the clinker composition is 3.5 – 4.0 % of kiln feed. Solid material out from the system is produced clinker. The clinker produced determination is based on LOI and moisture free. The calculations also consider internal dust circulation system.

Clinker produced + Dust Losses = kiln feed + coal ash + Dust insufflated (3.75 % of KF)

Clinker produced = (kiln feed + coal ash + Dust insufflated) - Dust Losses

= (109220 kg/hr. + 3723 kg/hr. + 4095.75 kg/hr.) - 7017.6 kg/hr.

Clinker production = **110,021.15 kg/hr.**

4.1.1.3. Heat balance Analysis of pyro-process system

The heat balance calculation is basically a calculation where heat inputs and outputs are measured, calculated and compared. The heat balance calculation provides a snap shot of the specific heat consumption of the kiln system with the kiln in stable operating conditions.

Performing Heat balance on pyro-processing system can offer extremely useful information on the thermal performance of the system (Madlool , N. A., et al. (2011). The basis of this heat balance is the experimental observation written as the first law of thermodynamics which implies that Energy can change from one form to another but the total amount remains constant. The heat balance is done based on coal firing quantity, measured air flow rates and temperature

Therefore; **Heat input = Heat output**

Unnecessary energy losses can be easily detected, the principle of heat balance was performed for kiln, preheater and for grate cooler.

Methods of Testing Calculations

When analyzing the pyro-processing system thermodynamically, several assumptions are commonly made to simplify the analysis and focus on key aspects of the process. These assumptions may vary depending on the specific analysis and the level of detail required. Here are some common assumptions(Ali Khalifa 2019):

- The system is assumed to be steady state, steady flow & open. From a theoretical point of view a proper balance can only be made if the system runs at steady conditions. E.g. during heating-up heat is stored in the system and there is no balance between input and output (input > output)
- Kinetic & Potential energy changes of input and output materials are negligible.
- Ambient conditions are constant throughout the study i.e. $T = 26^{\circ}C$ (299 K)
- Raw material and coal material composition do not change & feed rate of both are constant.
- The natural convection is taken into account as the velocity of atmospheric air is ≤ 3 m/s.
- Average kiln surface temperature does not change throughout the study.
- The gases inside the kiln are assumed to be ideal gases

Latent heat: - Latent heat is the amount of heat added to or removed from a substance to produce a change in phase

Sensible heat: - The heat added to or removed from a substance to produce a change in its temperature is called sensible heat

- Heat inputs

1. Heat of combustion (Q_c)
2. Heat of kiln feed (Q_{KF})
3. Sensible heat of coal (Qs, c)
4. Sensible heat of cooling air (Qs, c, a)
5. Sensible heat from primary Air ($Q_{p, a}$)

- **Heat output:**

1) Heat of formation / heat of clinker reaction (Q r)

2) Heat loss through preheater exit gas (Q p, exh)

3) Heat loss due to ESP (Q esp)

4) Heat loss due to water evaporation (Qw,e)

5) Heat loss through clinker (Qc,p)

6) Heat loss through radiation and convection (Qr&c)

7) Heat loss due to incomplete combustion (Qi,c)

a) Heat Input

1. Heat from combustion of coal (Qc)

The heat from the combustion of coal (Qc) is an important parameter to consider for kiln firing and secondary firing or pre-calciner. Qc represents the heat released per unit mass of coal burned and is typically measured in units of kilocalories per kilogram of clinker (kcal/kg clinker).

Q c = F * CV / P (kcal/kg clinker) ……………………………………………………..(5.4)

Q c: Heat from combustion of coal (kcal/kg clinker)

F = Fuel consumption (main burner and Calciner), (kg f /hr.)

CV: Calorific value or heating value of the coal ($kcal/kg_f$)

P = clinker production (kg clinker/hr.)

Table 4.12: Coal feed rate percentages to main burner and calciner

Main burner 40 % SA coal	7300 kg/hr.	F = 21300kg/hr.
Calciner burners 60 % (50%SA +50%LC)	14000kg/hr.	CV = 5000 kcal/kg
Production (P)	110,000 kg/hr.	
Q c = 968.2 kcal / kg clinker		

It's important to note that the actual heat transfer and efficiency of the combustion process can be influenced by various factors, such as the type of kiln, burner design, fuel properties, and operating conditions.

Specific Heat

The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius**.**

$Cp\ (Kcal/kg.^{\circ}\ C) = A + B*T*10^{-6} + C*T^{2}*10^{-9}$ ………………………………………… (5.5)

Table 4.13: Specific heat capacities of cement based components (Khalifa, S. A., & Alsadig, D. Y., 2019).

Components	A	B	C
CO_2	0.196	118	-43
H_2O	0.443	39	28
N_2	0.244	22	0
O_2	0.218	30	0
Air	0.237	23	0
Raw Meal	0.206	101	-37
Clinker	0.186	54	0
Hot Gas	0.237	23	0
Coal	0.262	390	0

1. **Sensible heat of Raw meal (Kiln feed)**

The sensible heat of raw meal, or kiln feed; the amount of heat energy contained in the material that can be transferred or exchanged during a temperature change without undergoing a phase change. It represents the thermal energy stored in the raw meal due to its temperature.

Q_{KF} = M * Cp * (T kf - Tr) / P ………………………………………………….. (5.6)

Q_{KF}	Sensible heat of kiln feed	fuel kcal / kg clinker
M	kiln feed flow rate	172,000 kg_{raw} / hr.
C p	Specific Heat of Raw meal	0.214 kcal / kg_{raw} ˚C
T_{kf}.	Kiln feed temperature	80 ˚C
T r	Reference Temperature	26 ˚C
P.	Clinker production	kg clinker /hr.

Q_{KF} = 1.56 * 0.214 * 54 = 18.56 **kcal / kg clinker**

2. **Sensible heat from coal**

It represents the thermal energy stored in the coal due to its temperature

$Q_{s.c} = M * C_P * (T_{f.} - Tr_{.)}$ ╱ P ………………………………………………………… (5.7)

$Q_{S.C}$	Sensible heat of fuel	kcal / kg clinker
M	Fuel flow rate (Main burner + Calciner)	21300 kg_f / hr.
C p	Specific Heat capacity of Fuel	0.287kcal / kg_f˚C
T_f	Fuel temperature	65 ˚C
T_r	Reference Temperature	26 ˚C
P.	Clinker Production	110,000 kg clinker / hr.

Q c, s = 21300*0.287*39╱110,000 **= 2.17 kcal / kg clinker**

3. **Sensible heat from cooling Air**

Sensible heat from cooling air ; the amount of heat energy that is removed or extracted from air during the cooling process, without any phase change occurring It represents the thermal energy that is transferred from the air to the cooling system or environment.

$Q_{s,c,a} = M_{s,c,a} * C_P\ s, c, a * T_{c,a} - T_{ref})$……………………………………………..(5.8)

M s, c, a (mass of cooling air) = V c, a* ρ s, c, a

V c, a ; volumetric flow rate of cooling air.

ρ c, a density of cooling air which is 1.22 kg/m^3

M s, c, a = 200584.4 m^3 / hr.×1.22kg/m^3 =244713 kg/h

$C_{P,a}$ = 0.237 kcal/kg ˚C

$T_{co, air}$ Temperature of cooling Air 37 ˚C

Q s, c, a = (244713kg/hr. * 0.237kcal/kg ˚C *11˚C) / 112940kg/hr. = **5.23 kcal / kg clinker**

OR; $Q_{s, c, a}$ = (2 kg air (5.0) kg clinker * 0.237kcal/kg ˚C *11˚C) = **5.23 kcal / kg clinker**

4. **Sensible heat from primary Air ($Q_{P, a}$)**

$Q_{p,s} = M_{p,a} * C_{P\ P,a} * (T_{p,a} - T_{ref})$………………………………………….. (5.9).

M_P, a = V_p , a * ρ_p, a

Where V_p, a is volumetric flow rate of primary air ρ_p, a is density of air which is 1.22 kg/m^3

M p, a Mass of primary air = 5004.1m^3/hr.×1.22kg/m^3 = 6105 kg/hr. = 0.0644 kg/kg Air

T p, a Temperature of primary air 55 ˚C

T ref Reference Temperature 26 ˚C

C_P , a Specific heat capacity of primary Air 0.238 kcal/kg ˚C

Q p, s = (6105 kg/hr. * 0.238kcal/kg ˚C * 29˚C) / 112940 kg/hr. = **0.373 kcal /kg clinker**

OR; $\mathbf{Q_{p,a} = M_{p,a} * CP_{p,a} (T_{p,a} - Tr) =}$ 0.0555 kg air/kg clinker*0.238kcal/kg ˚ C * 29 ˚ C

$\mathbf{Q_{p,a}}$ **= 0.383 kcal/kg clinker**

5. **Sensible heat of coal air (Q c, a)**

The sensible heat of coal air refers to the amount of heat energy contained in the mixture of coal and air. It represents the thermal energy stored in the combination of coal particles and the surrounding air due to their respective temperatures. To calculate the sensible heat of coal air, we would need to consider the individual contributions of the coal and the air, and then account for their combined effect. The calculation involves determining the sensible heat of the coal and the sensible heat of the air separately, and then adding them together.

$Q_{c,a} = M_{c,a} \times Cp_{c,a} \times \Delta T$………………………………………………………….. (6.0)

$M_{c,a} = V_{c,a} \times \rho_{c,a}$ but $V_{c,a}$ = (4440+3960+3770) m^3/hr. = 12170 m^3/h

$M_{c,a}$ = 12170m3/h ×1.22 kg/m^3 = 14847.4 kg/hr. ($\rho_{c,a}$ = 1.22 kg/m3)

$Cp_{c,a}$ = 0.238 kcal/kg ˚C and temperature of coal air = 65 ˚C

$Q_{C,a}$ = 14847.4 kg/hr.* 0.238kcal/kg ˚C *(65 ˚C –26 ˚C) / 110000 kg/hr. = **1.252 kcal/kg clinker**

6. **Sensible heat of false air ($Q_{S,fa}$)**

$Q_{s,f,a} = M_{s,f,a} * Cp_{sf,a} * \Delta T$……………………………………………………….(6.1)

$M_{s,f,a} = V_{s,f,a} \times \rho_{s,f,a}$ where $V_{f,a}$ is volumetric flow rate of false air

$M_{s,f,a}$ = 107110 m^3/h×1.22 kg/m3 = 130674.2 kg/h

$Cp_{s,f,a}$ = 0.238 kcal/kg ˚C

Temperature of cooling air $T_{s,f,a}$ = 37 ˚C

$Q_{s,f,a}$ = (130674.2 kg/hr. * 0.238 kcal/kg ˚C * 11˚C)/112940 kg/hr. = **3.03 kcal/kg clinker**

OR ; $\mathbf{Q_{p,a} = M_{f,a}}$ $*C_{p,f,a} * (T_{f,a} - T_r)$ = 1.188 kcal/kg clinker *0.238 kcal/kg ˚ C * 11 ˚ C

$\mathbf{Q_{p,a}}$ **<u>= 3.1 kcal/kg clinker</u>**

Q_{total} = $Qc + Q_{k f} + Q_{s, c} + Q_{s, c, a} + Q_{p,s} + Q_{c, a} + Q_{s, f, a}$ = **998.4 kcal /kg clinker**

b) Heat output

1. Heat of formation / heat of clinker reaction (Q r)

The heat of formation takes into account all main reactions which occur when raw meal is transformed to clinker, as follows it involves Heat of dehydration of clay (endothermic) ¨ Heat of de carbonation of $CaCO_3$ + $MgCO_3$ (endothermic) and Heat of formation of clinker (exothermic) . It should be noted the raw meal chemistry affects the reaction heat; the heat absorbed by the process gets bigger as the LSF of minerals rises.

Q_r = 2.2 A + 6.48 M + 7.646 C – 5.1165 S– 0.59 F (Kcal / kg clinker)………………….. (6.2)

The following are expressed as percentages of loss free of clinker

A = %Al_2O_3, M = % MgO , C = %CaO , S = % SiO_2 , F = % Fe_2O_3 + % P_2O_5

Table 4.14: The chemical compositions of Clinker sample analyzed by XRF

Components	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI	K_2O	Na_2O
(%)	65.27	21.46	5.39	3.59	1.68	0.50	0.45	0.5	0.26

Q_r = 2.2 * 5.39 + 6.48 *1.68 + 7.646 *65.27 – 5.1165 *0.5– 0.59 *3.59 = **409.88 kcal/kg clinker**

2. Heat loss through preheater exit gas (Q p, e)

$Q_{p, e} = m_e * C_{p, e} * (T_e - T_r)$…………………………………………………………..(6.3)

Pitot measurement of exit gases = 64.86 kg/sec

Clinker production = 2640 tpd = (2640ton/day *1000kg/1ton) / 24hr.*3600 sec = 30.56 kg/sec

M_e = 64.86/30.56 = **2.122 kg / kg clinker**

OR

The amount of air leaves through Cyclone 1 Preheater outlet gas the pipe (volume flow rate) and the mass flow rate can be calculated as **;** Q = $A \times v$ = 7.065 m^2 × 22.23 m/s *3600sec/hr.) = <u>565,397.82 m^3/hr.</u>

$m = \rho \times V$ = 0.4486 kg/m^3 × 565397.82 m^3/hr. = 253,637.5 kg/hr.

Kg air /Kg clinker = 253,637.5 kg/hr. /(110 ton/hr *1000 kg clinker /1ton) = **2.306 kg air/kg** clinker

Exit gas composition: O_2 = 5 %, CO_2 = 28 %, CO = 0.02 %

Assuming balance gases as N_2 = 100 – (O_2 + CO_2 +CO) = 100- 33.02 = 66.98 %

Table 4.15: Exit gas composition converting to weight fraction

Gas	Volume fraction	Weight fraction	Weight %
O_2	0.05	0.05*32/22.4 = 0.071	4.87
CO_2	0.28	0.28*44/22.4 = 0.55	37.71
CO	0.0002	0.0002*28/22.4 = 0.00025	0.017
N_2	0.6698	0.6698*28/22.4 = 0.837	57.40
Total	1.0	1.4583	99.997

The specific heat of exit gas is the sum of specific heats of individual gas components. Considering that waste gases in terms of weight percentage comprise of 4.87% O_2, 37.71% CO_2 and 57.9% N_2.

$$C_{P\,e} = \frac{4.87}{100}(0.218 + 30*410*10^{-6}) + \frac{37.71}{100}(0.196 + 118*410*10^{-6} - 43*410*10^{-9})$$

$$+ \frac{57.40}{100}(0.244 + 22*410*10^{-6})$$

$C_{p\,e}$ = 0.2459kcal / kg ˚C

Therefore $Q_{p.\,e}$ = 2.306 kg/kg clinker * 0.2459kcal/kg ˚C * (386 ˚C – 26 ˚C)

= **217.730 kcal /kg clinker**

3. Heat in clinker from cooling discharge

$Q_c = m * Cp_c * (T_c – T_r)$………………………………………………………………... (6.4)

m = wt. of clinker, C_p = mean specific heat of clinker, kcal/kg ˚C

T_c = temperature of clinker,= 138˚C

$C_p = 0.186+54*138*10^{-6} = 0.1935$ kcal/kg ˚C

$Q_{C} = 1*0.1935*(138-26)$ = **21.667 kcal / kg clinker**

4. **Heat in cooler exhaust air**

$Qc = m_{c\,e} * Cp_{c\,exh} *(T\ c\ exh – T\ r)$ ………………………………………………………… (6.5)

Pitot measurement of cooler exhaust air = 58.57kg/sec

Clinker output rate = 30.56 kg/sec

Therefore, $m_{c\,e}$ = 58.57/30.56 = 1.917 kg air /kg clinker

$Cp_{c\,e} = 0.237 + (23*264*10^{-6}) = 0.2437$ kcal/kg ˚C

Therefore, Qce = 1.92*0.2437*(290-26) = **123.53 kcal/kg clinker**

5. **Heat from cooler to coal mill**

$Q_{c,m} = m_{c,m} * Cp_{c,m} *(T_{c,m} – T_r)$ …………………………………………………….. (6.6)

$M_{c,m}$ = 0.194 kg/kg clinker $Cp_{c,m}$ = 0.247kcal/kg ˚C

$Q_{c,m}$ = 0.194 kg/kg clinker *0.247kcal/kg ˚C*(290 ˚C -65 ˚C) =**10.781 kcal/kg clinker**

6. **<u>Heat of evaporation of Raw Meal Moisture-</u>**

$Q_{e,r} = m_{m,r} * L$ ……………………………………………………… (6.7)

$Q_{e,r}$ = Heat Loss with Evap. of Water kcal / kg clinker

$M_{m,r}$ = Weight of moisture kg water / kg clinker

L = Heat of evaporation of moisture kcal/kg

Raw meal feed rate = 172 tph

Moisture in raw meal = 0.8 %

Therefore, weight of moisture = 1.564*0.8/100 = 0.0125 kg water/kg clinker

L – Latent heat of water evaporation = 540 kcal/kg

Therefore, heat of evaporation of raw meal moisture = 0.0125*597 = **7.468 kcal/kg clinker**

7. **Heat of evaporation of coal moisture –**

The heat of evaporation of coal moisture refers to the amount of heat energy required to convert a unit mass of water in coal from the liquid state to vapor during the process of evaporation. This heat value, also known as the latent heat of vaporization,

Heat of Evaporation = Moisture Content * Heat of Evaporation of Water

$Q_{e,cm} = m_{m,c} * L$……………………………………………………………………..(6.8)

Coal consumption = 21300 kg coal/110000kg clinker = 0.194 kg/kg clinker

Moisture in coal = 2.57 %

Moisture in coal in terms of kg/kg clinker = 0.194 * 2.57/100 = 0.005 kg water / kg of clinker

Heat of evaporation of coal moisture = 597 kcal/kg = 0.005kg H_2O/kg clink.*597 kcal/kg

= 2.985 kcal/kg clinker

➢ Radiation and Convection Heat Losses

In practice it is quite convenient to treat both, radiation and convection heat transfer together. Although the physical laws of these two heat transfer phenomena's are different they are usually given as a total

Radiation Heat Transfer

Radiation heat transfer occurs through Electromagnetic waves emitted by surface. The rate of heat loss due to radiation can be calculated using the Stefan-Boltzmann law

i. **Heat losses for surface of kiln**

In the kiln, hot raw mixture comes from the pre-heater and calciner.

It again gets heated by the energy produced from the burning of the fuel, resulting in more energy losses in the form of radiation and convection. These thermal energy losses can be observed from the walls of the kiln which is about 64 m long. The energy losses were studied at a distance of every 2 m along the wall of the kiln. Temperatures were measured outside the surface of the kiln with the help of Infrared thermometer. After the test, losses are calculated with the help of Stefan-Boltzmann law and convection law formula.

Radiation heat transfer depends on the surface temperature and the emissivity e (0...1).

The surface loss consists of radiation and convection losses.

Radiation losses (Q_r) = $\delta * \varepsilon * A * (T_s^4 - T_A^4)$, kcal /hr. (Chakrabarti, B. K., 2002) ………………… (6.9)

Where

δ – = $Stephen\ Boltzman\ sconstan$ (4.88 x 10^{-8} kcal / m^2 K) ; ε – Surface emissivity (0.9 $for\ rough\ oxidized\ steel$)

T_{s} - is the shell temperature in (Kelvin)

$T_{ambient}$ - the ambient temperature when the surroundings are a long distance from the shell (Kelvin)

Convection losses (Q_c), for wind velocity less than 3 meter per second

$Q_c = 80.33 * [(T_A + T_S)/2]^{-0.724} * [(T_S - T_A)]^{1.33}$ * surface area, kcal/hr.(Vijay Bhan,2016) ……… (7.0)

The kiln has length of 64 m and a diameter 4.6 m. throughout the length the kiln diameter is uniform. However, depending on the zone of the kiln, the shell temperature is different.

$A_{Kiln} = \pi \times D_{Kiln} \times L_{Kiln}$ (at each meter of the kiln surface)……………….. (7.1) .

Where D is the diameter of the kiln and L – length of the kiln

For the length from 0 - 2m meter from kiln outlet. The average shell temperature becomes 385˚ C or 658 K

Elemental areas of kiln ;

$(A_{Kiln})_1 = \pi * 4.6m * 2m = 28.9\ m^2$, $(A_{Kiln})_2 = \pi * 4.6m * 2m = 28.9\ m^2$

So, total elemental area of a kiln from A_1 to A_{32} = π* 4.6m* 32m = **924.8 m^2**

$Q_{rad,1}$(radiation heat losses,1) = $4.876*0.9*10^{-8} * (658^4 - 299^4)$ Kcal/h/m^2 = **7875. 65 Kcal/h/m^2**

$Q_{nc,1}$(conv. heat losses,1) = $80.33*[(658+299)/2]^{-0.724}*[(658–299)]^{1.33}$ = **2306.32 Kcal/hr./m²**

Total Surface heat losses ($Q_{T,1}$)= 7875.65 Kcal/h/m^2 +2306.32 Kcal/h/m^2 **= 10181.97 Kcal/h/m^2**

So, radiation heat losses = $\frac{(10181.97 \text{ Kcal/h/m}^2 * 28.9\text{m}^2)}{(110 \text{ ton of clinker /hr.} * 1000 \text{ kg clinker/1ton})}$ = **2.675 Kcal/kg clinker**

$Q_{\text{radiation heat losses, (1 – 32)}}$ = 136,993 Kcal/hr/m^2

$Q_{\text{Convection heat losses, (1 – 32)}}$ = 52,755 Kcal/hr/m^2

Q_{Total} surface heat losses =$Q_{\text{radiation heat losses,(1 – 32)}}$ +$Q_{\text{Convection heat losses, (1 – 32)}}$ = **189,747 Kcal/hr/m^2**

Kiln Output = 2640*1000/24 = 110,000 kg/hr.

Therefore specific radiation and Convection losses from kiln shell = $\frac{189{,}747 \text{ Kcal/ hr.m}^2 * 28.9\text{m}^2}{110{,}000 \text{ kg clinker/hr}}$

= 49.86 Kcal /kg clinker

ii. Heat losses for surface of preheater and pre-calciner

In the preheater and calciner, the prepared raw mixture consisting of limestone, rhyolite, etc. gets dried with the internal passage of the flue gases. The prepared mixture was passed through the five-stage cyclone preheater (from C1 to C5) and the calciner. The flue gases were generated with the burning of fossil fuel in the calciner and kiln. As a result, the heat is lost through the preheater and calciner via the radiation and convection heat transfer. At various points of the surface of the cyclone & calciner, temperature was measured with the help of the pyrometer. Oxygen content in the flue gas was measured at outlet of the Cycloner with the help of gas analyzer.

The raw mix can be calcined 93 to 94% in the calciner before reaching to the kiln inlet. This result in the lower consumption of the energy per ton of the clinker produced in the cement production unit (Dulaimi, Z., Hammed, H., & Alfahham, M., 2018)

The surface heat loss of preheater and pre-calciner consists of radiation and convection losses.

Radiation losses (Qr) = δ *ε * A* (Ts4 – TA4), kcal /hr.

δ – = $Stephen\ Boltzman\ sconstan$ (4.88 x 10 -8 kcal / m2 K) , ε – Surface emissivity (0.9 $for\ rough\ oxidized\ steel$)

T s - is the shell temperature in (Kelvin)

T ambient - the ambient temperature when the surroundings are a long distance from the shell (Kelvin)

Convection losses (Q c), for wind velocity less than 3 meter per second

Qc = 80.33 * [(TA + TS) / 2]-0.724 * [(TS – TA)] 1.33 * surface area, kcal/hr.

The Cyclones has different length and diameters from C-1 to C-5 and precalciner .Throughout the length of the cyclone diameters are non-uniform and their shell temperatures also different.

Calculating radiation and convection heat loss from the surfaces of each cyclone preheater stage in a five-stage cyclone preheater is justified for several reasons:

Energy Efficiency: By quantifying heat loss, it helps assess the overall energy efficiency of the preheating system. Identifying areas with significant heat loss allows for targeted improvements in insulation, design, or operational practices to minimize energy waste and increase efficiency.

Performance Evaluation: Heat loss from preheater surfaces can impact the performance of the system. Calculating heat loss helps evaluate whether the preheater is operating within the desired temperature range. Excessive heat loss may indicate inefficiencies or issues requiring corrective actions.

Heat Recovery Potential: Understanding heat loss helps identify opportunities for heat recovery.

Cost Analysis: Heat loss represents wasted energy, resulting in increased operating costs. By quantifying heat loss, it becomes possible to estimate the financial impact of the losses, evaluate the cost-effectiveness of potential mitigation measures, and justify investments in energy-efficient technologies or maintenance activities.

Table 4.16: Heat Losses result due to Radiation and Convection from a Kiln with a dimension of Ø 4.6 X 64MM

Ambient temperature			26	°C										
S N	Location, m	Kiln Dia, m	Kiln Length, m	Element area, m2	Clinker, tph	Ambient Temp °K	Surface Temp, °C	Surface Temp,°K	Radiation losses(Qr) Kcal/hr/m^2	Convection losses(natural convection,Qnc) Kcal/hr/m^2	Radiation,Kcal/h/m^2 Qt	Radiation, Kcal/ kg clinker	Heat transfer coefficient(Radiation)	Heat transfer coefficient (Radiation)
1	0 to 2	4.60	2	28.90	110.00	299.00	385	658	7875.65	2306.32	10181.97	2.675	25.510	24.214
2	2 to 4	4.60	2	28.90	110.00	299.00	315	588	4895.10	1826.08	6721.19	1.766	19.696	18.557
3	4 to 6	4.60	2	28.90	110.00	299.00	310	583	4718.93	1791.50	6510.44	1.711	19.322	18.193
4	6 to 8	4.60	2	28.90	110.00	299.00	291	564	4089.66	1659.85	5749.51	1.511	17.946	16.857
5	8 to 10	4.60	2	28.90	110.00	299.00	246	519	2833.27	1347.14	4180.41	1.098	14.976	13.978
6	10 to 12	4.60	2	28.90	110.00	299.00	234	507	2548.86	1263.75	3812.61	1.002	14.250	13.276
7	12 to 14	4.60	2	28.90	110.00	299.00	188	461	1631.28	945.73	2577.02	0.677	11.709	10.822
8	14 to 16	4.60	2	28.90	110.00	299.00	372	645	7244.56	2217.76	9462.32	2.486	24.348	23.082
9	16 to 18	4.60	2	28.90	110.00	299.00	346	619	6091.97	2039.74	8131.71	2.137	22.137	20.930
10	18 to 20	4.60	2	28.90	110.00	299.00	377	650	7482.82	2251.86	9734.68	2.558	24.790	23.513
11	20 to 22	4.60	2	28.90	110.00	299.00	249	522	2907.53	1367.99	4275.53	1.123	15.161	14.158
12	22 to 24	4.60	2	28.90	110.00	299.00	257	530	3111.91	1423.62	4535.53	1.192	15.665	14.646
13	24 to 26	4.60	2	28.90	110.00	299.00	317	590	4966.84	1839.91	6806.75	1.788	19.848	18.704
14	26 to 28	4.60	2	28.90	110.00	299.00	366	639	6965.86	2176.79	9142.65	2.402	23.824	22.572
15	28 to 30	4.60	2	28.90	110.00	299.00	245	518	2808.81	1340.19	4148.99	1.090	14.914	13.919
16	30 to 32	4.60	2	28.90	110.00	299.00	357	630	6562.28	2115.20	8677.48	2.280	23.054	21.822
17	32 to 34	4.60	2	28.90	110.00	299.00	339	612	5805.44	1991.62	7797.06	2.049	21.568	20.376
18	34 to 36	4.60	2	28.90	110.00	299.00	344	617	6009.11	2026.00	8035.10	2.111	21.974	20.771
19	36 to 38	4.60	2	28.90	110.00	299.00	341	614	5886.31	2005.38	7891.69	2.074	21.730	20.533
20	38 to 40	4.60	2	28.90	110.00	299.00	278	551	3694.20	1569.59	5263.79	1.383	17.047	15.985
21	40 to 42	4.60	2	28.90	110.00	299.00	281	554	3783.02	1590.43	5373.45	1.412	17.251	16.183
22	42 to 44	4.60	2	28.90	110.00	299.00	236	509	2594.88	1277.64	3872.52	1.018	14.369	13.391
23	44 to 46	4.60	2	28.90	110.00	299.00	249	522	2907.53	1367.99	4275.53	1.123	15.161	14.158
24	46 to 48	4.60	2	28.90	110.00	299.00	242	515	2736.24	1319.33	4055.58	1.066	14.731	13.741
25	48 to 50	4.60	2	28.90	110.00	299.00	233	506	2526.05	1256.80	3782.85	0.994	14.190	13.218
26	50 to 52	4.60	2	28.90	110.00	299.00	239	512	2664.94	1298.49	3963.43	1.041	14.549	13.565
27	52 to 54	4.60	2	28.90	110.00	299.00	230	503	2458.43	1235.97	3694.40	0.971	14.013	13.047
28	54 to 56	4.60	2	28.90	110.00	299.00	231	504	2480.83	1242.92	3723.75	0.978	14.072	13.104
28	56 to 58	4.60	2	28.90	110.00	299.00	243	516	2760.29	1326.28	4086.58	1.074	14.792	13.800
28	58 to 60	4.60	2	28.90	110.00	299.00	306	579	4581.23	1763.82	6345.04	1.667	19.026	17.905
29	60 to 62	4.60	2	28.90	110.00	299.00	308	581	4649.72	1777.66	6427.39	1.689	19.173	18.049
30	62 to 64	4.60	2	28.90	110.00	299.00	310	583	4718.93	1791.50	6510.44	1.711	19.322	18.193
Total >>				924.88					136993	52755	189747	**49.86**	**580.12**	545.260

The total heat losses calculations result from the kiln due to radiation and convection are indeed **49.86 Kcal/kg clinker.**

Table 4.17: Heat Losses result due to Radiation and Convection from Cyclone and Preheater

CYCLONES		Dcy ,Dco	Lc	do	Lo	Surface area (m^2)	Clinker tph	Ave.surface temp.	Surface temp	Radiation losses (Qr) Kcal/hr/m2	Convection losses Kcal/hr/m^2	Radiation,Kcal/ h/m^2 Qt	Radiation, Kcal/ kg	Heat transfer coefficient
		(m)	(m)	(m)	(m)			˚C	˚ K					
Cycl.1A	**Cyl**	5.9	8.95			165.80	110	85.00	358.00	370.09	274.25	644.34	0.971	7.294
	Cone.	5.4		0.9	6.2	61.36	110	114.00	387.00	633.61	452.36	1085.97	0.606	8.373
Cycl.1B	**Cyl.**	5.4	8.95			151.75	110	100.00	373.00	498.71	364.66	863.37	1.191	7.837
	Cone.	5.4		0.9	6.2	61.36	110	108.00	381.00	573.97	414.44	988.40	0.551	8.139
Cycl.2	**Cyl.**	8.3	7.5			195.56	110	176.00	449.00	1432.83	863.61	2296.45	4.083	11.108
	Cone.	7.184		1.15	8.6	112.58	110	129.00	402.00	795.32	549.03	1344.35	1.376	8.979
Cyc.3	**Cyl.**	8.3	7.5			195.56	110	137.00	410.00	889.31	601.50	1490.81	2.650	9.316
	Cone.	7.184		1.15	8.6	112.58	110	210.00	483.00	2037.59	1097.36	3134.95	3.209	12.877
Cyc.4	**Cyl.**	9	7.3			206.40	110	188.00	461.00	1631.28	945.73	2577.02	4.835	11.709
	Cone.	7.9		1.33	9	130.49	110	178.00	451.00	1464.82	877.27	2342.09	2.778	11.206
Cyc.5	**Cyl.**	8.7	7.5			204.99	110	253.00	526.00	3008.56	1395.81	4404.36	8.208	15.412
	Cone.	7.9		1.33	9.2	133.39	110	289.00	562.00	4027.01	1645.97	5672.98	6.879	17.805
Calcine	**Upper C**	6.4	13.7			275.45	110	165.00	438.00	1264.37	788.84	2053.20	5.141	10.577
	Lower C	6.4	13.5			271.43	110	188.00	461.00	1631.28	945.73	2577.02	6.359	11.709
	Cone.	6.4		2.35	6.3	86.59	110	197.00	470.00	1790.65	1007.62	2798.28	2.203	12.177
													51.041	
	Material pipes													
	Cyc.1A	0.8	7.8			19.6035382	110	132.00	405.00	829.92	568.64	1398.56	0.249	9.104
	Cyc.1B	0.8	7.8			19.6035382	110	98.00	371.00	480.64	352.37	833.01	0.148	7.763
	Cyc.2	1	8.9			27.9601746	110	200.00	473.00	1845.85	1028.30	2874.15	0.731	12.336
	Cyc.3	1	12.5			39.2699082	110	290.00	563.00	4058.25	1652.91	5711.16	2.039	17.875
	Cycl.4	1	17.9			56.2345085	110	238.00	511.00	2641.45	1291.54	3932.99	2.011	14.489
	Cycl 5	1	11.3			35.499997	110	269.00	542.00	3436.33	1507.05	4943.38	1.595	16.444
													6.773	
	R.DUCTS													
	C1A	2.5	7.8			61.2610567	110	88.00	361.00	394.56	291.98	686.54	0.382	6.628
	C1B	2.5	7.8			61.2610567	110	90.00	363.00	411.22	303.91	715.12	0.398	7.472
	C2	3.8	13.1			156.388482	110	177.00	450.00	1448.77	870.44	2319.21	3.297	11.157
	C3	4.3	12.8			172.91326	110	135.00	408.00	865.29	588.33	1453.62	2.285	9.231
	C4	4.4	15.1			208.727416	110	182.00	455.00	1530.10	904.61	2434.71	4.620	11.405
	C5	4.7	16			236.247768	110	234.00	507.00	2548.86	1263.75	3812.61	8.188	14.250
													19.171	
	ROOF													
	C1.A	5.9				22.4309715	110	85.00	358.00	370.09	274.25	644.34	0.131	7.294
	C1.B	5.9				22.4309715	110	87.00	360.00	386.34	286.05	672.39	0.137	7.365
	C2	10.9				81.9720063	110	100.00	373.00	498.71	364.66	863.37	0.643	7.837
	C3	8.3				39.5840674	110	113.00	386.00	623.47	446.01	1069.48	0.385	8.333
	C4	9				48.4119428	110	127.00	400.00	772.69	536.01	1308.69	0.576	8.896
	C5	8.7				42.0973416	110	194.00	467.00	1736.50	986.97	2723.47	1.042	12.019
	Calciner	6.4				32.1699088	110	183.00	456.00	1546.68	911.46	2458.14	0.719	11.456
													2.915	

The total radiation and convection heat losses from the cyclone and precalciner being calculated as **79.90 Kcal/kg clinker.** This value of 79.90 Kcal/kg clinker heat lost that is not effectively utilized in the clinker production process. The total radiation and convection heat loss from the preheater cyclone is higher and the figure 4.2 also indicates that the rust area of the cyclones is exposed to high surface temperatures; it is indeed recommended to install insulating bricks to reduce heat losses and improve the performance of the cyclones.

iii. Heat losses for surface of grate cooler

The residence time of clinker in the cooler plays a crucial role in achieving maximum clinker cooling while minimizing the cooling air volume. The specific consumption of heat is an important indicator for measuring the thermal energy consumed in clinker production and assessing the performance of the cooler (Amole, M. O., 2018). The grate cooler has a length of 22 meters and a width of 4 meters, resulting in a total surface area of 88.8 square meters.

Cooler CCR side

$Q\ r_L$ (CCR side) = 17802.05481Kcal/hr./m^2 ; $Q\ c_L$ (CCR side) = 11008.2 Kcal/hr./m^2

Total radiation and convection heat loss from CCR side; $Q_{r\,L} + Q_{c\,L}$ = 28,810.3 Kcal/hr./m^2 = **1.057 Kcal /kg clinker**

Cooler combined shade side

$Q_{r\,R}$ (combined shade side) = 15,618.77 Kcal/hr./m^2

$Q_{C\,R}$ (combined shade side) = 10,356.4 Kcal/hr./m^2

Total radiation and convection heat losses from cooler combined shade side; ($Q_{r\,R} + Q_{C\,R}$) = 25,975.2 Kcal/hr./m^2 = **0.953 Kcal/kg clinker**

Cooler roof

Q r = 16,324.4 Kcal/hr./m; Q c = 11,163 Kcal/hr./m2

Total radiation and convection heat losses from cooler roof; (Q r + Q_C) = 27,487.3 Kcal/hr./m2 = **1.009 Kcal/kg clinker**

Total heat losses from cooler due to radiation and convection **= 3.02 Kcal / kg clinker**

To optimize the performance of the grate cooler and reduce heat losses, various measures can be considered, such as improving insulation, optimizing air distribution, enhancing heat recovery systems, and implementing efficient process control.

Table 4.18: Heat Losses calculated result due to Radiation and Convection from cooler (CCR side)

Cooler CCR side						
From kiln outlet	**Cooler body temp(K)**	**Elemental area ,m2**	**Radiation losses (Qr) Kcal/hr/m^2**	**Convection losses (natural con.,Qnc) Kcal/hr/m^2**	**Radiation Kcal/h/m^2 Qt**	**Radiation, Kcal/ kg clinker**
1	460.15	4.04	1616.002003	938.6	2554.6	0.0937
2	510.15	4.04	2620.886164	1284.2	3905.1	0.1433
3	478.15	4.04	1942.38961	1062.5	3004.9	0.1103
4	469.15	4.04	1774.501272	1000.5	2775.0	0.1018
5	456.15	4.04	1548.4781	911.2	2459.7	0.0903
6	423.15	4.04	1055.517012	687.6	1743.2	0.0640
7	416.15	4.04	964.7023173	641.0	1605.7	0.0589
8	411.15	4.04	902.5794988	607.9	1510.5	0.0554
9	400.15	4.04	773.6675559	535.8	1309.5	0.0481
10	392.15	4.04	686.3544493	484.2	1170.5	0.0430
11	386.15	4.04	624.2826461	445.9	1070.2	0.0393
12	374.15	4.04	508.532752	370.7	879.2	0.0323
13	371.15	4.04	481.2807843	352.3	833.5	0.0306
14	355.15	4.04	346.7086821	256.6	603.3	0.0221
15	348.15	4.04	293.2720444	216.5	509.8	0.0187
16	347.15	4.04	285.8965049	210.9	496.8	0.0182
17	338.15	4.04	222.3289051	161.7	384.0	0.0141
18	331.15	4.04	176.2731159	125.3	301.5	0.0111
19	329.15	4.04	163.6393134	115.2	278.9	0.0102
20	349.15	4.04	300.7114134	222.2	522.9	0.0192
21	343.15	4.04	257.0253335	188.7	445.7	0.0164
22	343.15	4.04	257.0253335	188.7	445.7	0.0164
	SUM(m^2	88.80	17802.05481	11008.2	**28810.3**	**1.0572**

Table 4.19: Heat Loss calculated result due to Radiation and Convection (cooler roof side)

	Cooler roof						Cooler combined shade side		
Cooler body temp(K)	Radiation losses (Qr) Kcal/hr/m^2	Convection losses (natural conv,Qnc) Kcal/hr/m^2	Radiation, Kcal/h/m^2 Qt	Radiation, Kcal/ kg clinker	Cooler body temp (K)	Radiation losses ,(Qr) Kcal/hr/m^2	Convection losses , (Qnc) Kcal/hr/m^2	Radiation, Kcal/h/m^2 Qt	Radiation, Kcal/ kg clinker
425.15	1082.31	701.0	1783.3	0.0654	474.15	1866.590307	1034.9	2901.5	0.1065
431.15	1164.97	741.3	1906.3	0.0700	448.15	1418.659244	856.5	2275.2	0.0835
423.15	1055.52	687.6	1743.2	0.0640	423.15	1055.517012	687.6	1743.2	0.0640
415.15	952.10	634.4	1586.5	0.0582	407.15	854.486237	581.6	1436.1	0.0527
418.15	990.19	654.3	1644.5	0.0603	403.15	807.7897401	555.4	1363.2	0.0500
416.15	964.70	641.0	1605.7	0.0589	404.15	819.3344158	561.9	1381.3	0.0507
404.15	819.33	561.9	1381.3	0.0507	387.15	634.429256	452.2	1086.6	0.0399
407.15	854.49	581.6	1436.1	0.0527	371.15	481.2807843	352.3	833.5	0.0306
400.15	773.67	535.8	1309.5	0.0481	374.15	508.532752	370.7	879.2	0.0323
398.15	751.34	522.9	1274.2	0.0468	371.15	481.2807843	352.3	833.5	0.0306
402.15	796.33	548.9	1345.2	0.0494	369.15	463.4761678	340.0	803.5	0.0295
404.15	819.33	561.9	1381.3	0.0507	373.15	499.3755681	364.5	863.9	0.0317
391.15	675.81	477.7	1153.6	0.0423	371.15	481.2807843	352.3	833.5	0.0306
394.15	707.69	497.0	1204.7	0.0442	363.15	411.7722184	303.8	715.6	0.0263
409.15	878.36	594.7	1473.1	0.0541	477.15	1923.260445	1055.6	2978.9	0.1093
383.15	594.31	426.9	1021.2	0.0375	355.15	346.7086821	256.6	603.3	0.0221
378.15	545.90	395.5	941.4	0.0345	383.15	594.3123338	426.9	1021.2	0.0375
371.15	481.28	352.3	833.5	0.0306	370.15	472.3424004	346.1	818.5	0.0300
364.15	420.21	309.8	730.0	0.0268	367.15	445.9585998	327.9	773.8	0.0284
360.15	386.86	286.0	672.8	0.0247	361.15	395.0972518	291.9	687.0	0.0252
353.15	331.11	245.0	576.2	0.0211	359.15	378.6970271	280.0	658.7	0.0242
346.15	278.58	205.3	483.9	0.0178	346.15	278.5844286	205.3	483.9	0.0178
	16324.40	**11162.9**	**27487.3**	**1.0086**		**15,618.77**	**10356.4**	**25975.2**	**0.9531**

Table 4.20: Summary of Thermal Energy Audit for pyro-processing Unit

	Equation	Mass kg/kg clinker	Temp (ΔT,°C)	CP (kcal/kg °C)	Result (kcal/kg Clin.)	(%)
Heat input						
Heat of fuel combustion/heat from the combustion of Coal; Q = CV(kcal/kg) * m (kg fuel/kg clink.)	mfuel * CV	0.194			968.20	96.97
Heat in kiln feed/	mf * CPf (Tf - Tr)	1.564	54	0.214	18.06	1.81
Heat in cooling Air/sensible heat from cooler air	mc,a * CPc, a (Tc,a - Tr)	2.000	11	0.238	5.23	0.52
Heat in primary Air/sensible heat from primary air	mp ,a* CP p,a (Tp, a - Tr)	0.056	29	0.238	0.38	0.04
Sensible heat of coal air	mc, a *Cp(Tc,a -Tr)	0.135	39	0.238	1.25	0.13
Sensible heat of false air	m f, a *C p ,f, a * (Tf,a – Tr)	1.188	11	0.238	3.11	0.31
Sensible heat of Fuel	mfuel * CP (Tfuel -Tr)	0.194	39	0.287	2.17	0.22
Total heat input					**998.40**	100.00
Heat output						
Heat of formation/heat of clinker rxn	2.2A + 6.48M + 7.646C - 5.1165S -0.59F				409.88	43.27
Heat in PH Exist Dust	md * CPd * (Td - Tr)	0.240	360	0.239	20.69	2.18
Heat in PH Exist Gas(C1)	me * CPe * (Te - Tr)	2.31	386	0.246	217.73	22.98
Heat in Clinker from Cooler Discharge	m * CPc * (Tc - Tr)	1.00	112	0.193	21.67	2.29
Heat in Cooler Exhaust Air	mce * CPce * (Tce - Tr)	1.92	264	0.244	123.51	13.04
Heat from cooler to coal mill-	m*Cp, c, m *(Tc ,m – Tr)	0.19	225	0.244	10.64	1.12
Heat in Evaporation of Raw meal moisture	m mr*L	0.0125			7.47	0.79
Heat of evaporation of coal moisture	m m, c* L	0.1940			2.98	0.31
Radiation and Conventional Losses	Kiln				49.86	5.26
	Preheater				79.90	8.43
	Cooler				3.02	0.32
Raw meal feed rate	172	tph		Total Output	**947.3394176**	100
Clinker output	110	tph				
amount (*mmr*)	1.564	kg/kg clinker				
Wt.of Moisture	0.0125	kg water/kg clinker				
Heat of evaporation of moisture	597	kcal/kg				

The total energy used in the process is **998.40 kcal/kg clinkers**, with coal being the main heat source contributing a total heat of 968.20 kcal/kg clinker, which accounts for approximately **96.97%** of the total heat input. Heat input output difference of 51 kcal /kg clinker

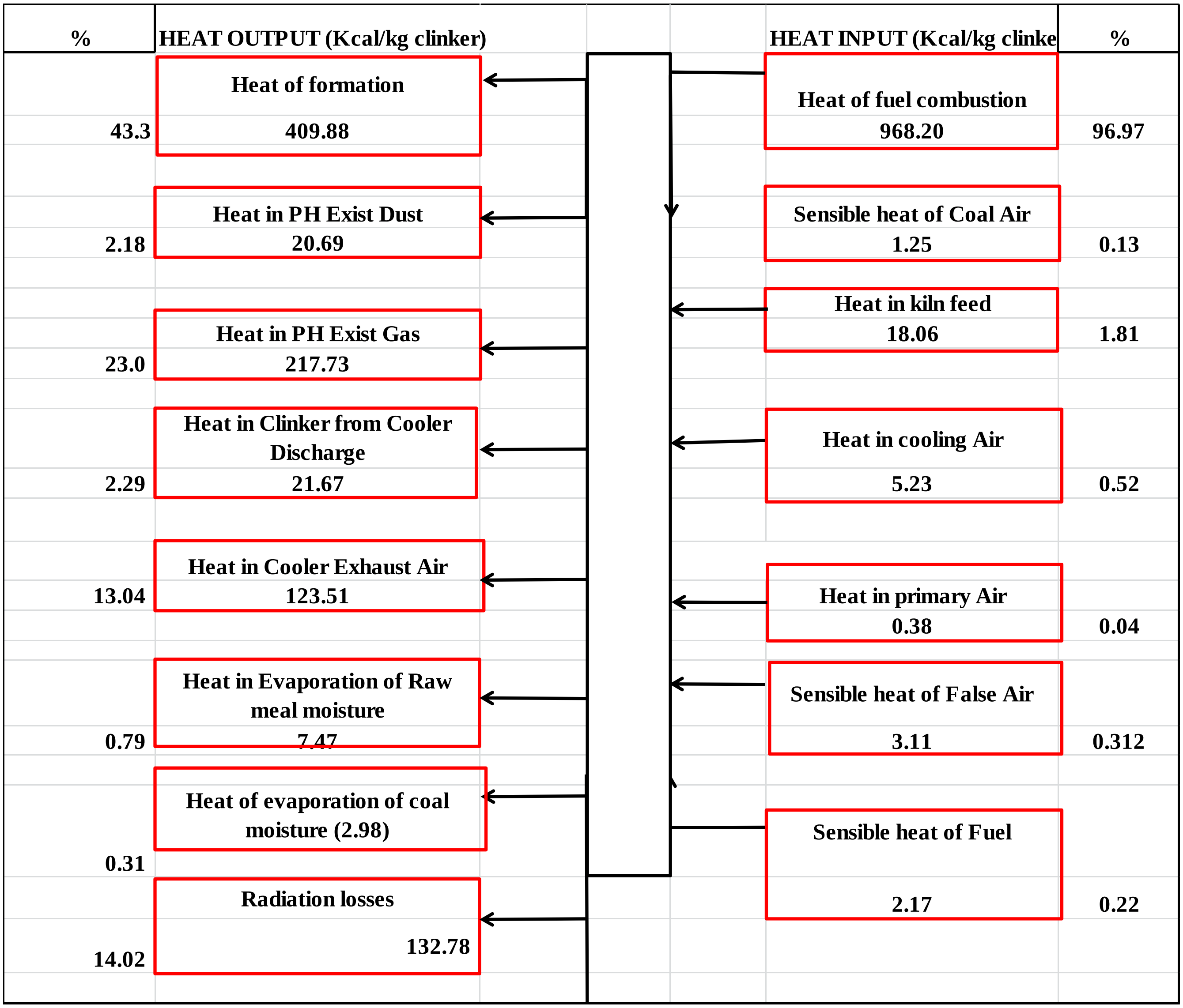

Figure 4.6: Representation of the input and output energy flows in a pyro-processing system

4.2. ELECTRICAL ENERGY AUDIT

In the cement industry, electrical motors are indeed the primary consumers of electrical energy. They are responsible for driving various equipment and machinery used in the production process. These motors are used for a wide range of applications, including mills, fans, kilns, bucket elevators, conveyors, compressors, pumps, and more. At National Cement, with a significant number of motors more than 800, spanning a range of power consumption from a few KW to MW, The efficiency operation of these motors is crucial for optimizing energy consumption and reducing overall electrical energy costs in cement plants.

The research focused on high-capacity motors is a strategic approach, considering their significant energy consumption and continuous operation throughout the plant's operational hours. The drop in efficiency of these motors can have a substantial impact on the overall energy consumption of the cement plant

4.2.1. Specific Energy Consumption of National Cement Plant

The NCSC overall specific energy consumption is analyzed from the raw data collected from production and electrical departments. The four year data from 2018/2019 to 2021/2022 for the main process units starting from Raw Mill to cement mill was considered. In these periods majorly South African coal is used as a fuel energy source and the total consumption in kWh is **3,034,496,674.71** and the electric energy consumption for two Crushers, Raw Mill, Coal Mill, Kiln , two cement mills and packaging units to produce two types of cement products OPC and PPC is found **519,633,311 kWh** of electricity. Total energy consumption is then **3,554,129,985.71kWh** the total cement production in these period is **4,339,730Ton** of cement, hence;

$$\text{Specific energy consumption in KWh/ton of cement} = \frac{\text{Total KWh}}{\text{Total cement in Ton}}$$

$$= \frac{(3{,}554{,}129{,}985.71)\ \text{KWh}}{4{,}339{,}730\ \text{Ton}} = \mathbf{818.97\ KWh/Ton\ Cement}$$

Table 4.21: Specific energy consumption of Major Equipment Summary

	Specific energy consumption of Major Equipment's in (KWh/ton)			
Year	**Raw mill**	**Coal Mill**	**Kiln**	**Cement mill #1&2**
2018-2019	24.81	31.1	39.63	52.02
2019-2020	25.12	27.34	41.44	50.58
2020-2021	25.76	23.24	42.69	48.88
2021-2022	25.85	25.32	44.48	51.09
AVE.	25.39	26.75	42.06	50.64

4.2.2. Analyzing the energy consumption and material production relationship

Controlling energy consumption and managing costs are crucial steps in conducting energy efficiency surveys. In recent years, there have been numerous studies focusing on energy efficiency and energy utilization in various industries (Tanaka 2008, Gielen and Taylor 2009, Palamutcu 2010, Bunse, Vodicka et al. 2011, Giacone and Mancò 2012). Energy consumption, SEC (specific energy consumption), a material production amount and energy efficiency are calculated from these literature studies(Kannan and Boie 2003)

Table 4.22 presents the energy consumption and material production data for the factory. The table specifically focuses on the electrical energy consumption of the factory. Total energy consumption is the cumulative sum of the electrical energy consumed over a 12-month period, all measured in the same units. Similarly, material production represents the total output of materials during the same 12-month timeframe, also measured in consistent units. The material production and energy consumption amounts are calculated by the constants **a** and **b.** Using the least squares method and the constants a and b determined through the recursive least squares method, it is possible to calculate the energy equation. The energy equation obtained through this method can be expressed as a linear equation. The cumulative sum (CUSUM) technique can be employed to create a CUSUM graph based on the results. Using the least squares method, the linear (Energy) equation is as follows (Zhang, Deng et al. 2011, Bastola and Sapkota 2015, Sun and Anwar 2015)

Table 4.22: Calculation of the material production and energy consumption values table (Tanaka 2008, Gielen and Taylor 2009, Palamutcu 2010, Bunse, Vodicka et al. 2011, Giacone and Mancò 2012)

Period	**Material production value, P_i**	**Current energy consumption value, E_i**	**Theoretical energy consumption value, ($a + b*P_i$)**	**Difference value, D_i**	**Sum of CUSUM value, CS_i**
January	P_1	E_1	TE_1	$D_1 = (E_1 - TE_1)$	$CS_1 = (D_1)$
February	P_2	E_2	TE_2	$D_2 = (E_2 - TE_2)$	$CS_2 = (CS_1 + D_2)$
March	P_3	E_3	TE_3	$D_3 = (E_3 - TE_3)$	$CS_3 = (CS_2 + D_3)$
April	P_4	E_4	TE_4	$D_4 = (E_4 - TE_4)$	$CS_4 = (CS_3 + D_4)$
May	P_5	E_5	TE_5	$D_5 = (E_5 - TE_5)$	$CS_5 = (CS_4 + D_5)$
June	P_6	E_6	TE_6	$D_6 = (E_6 - TE_6)$	$CS_6 = (CS_5 + D_6)$
July	P_7	E_7	TE_7	$D_7 = (E_7 - TE_7)$	$CS_7 = (CS_6 + D_7)$
August	P_8	E_8	TE_8	$D_8 = (E_8 - TE_8)$	$CS_8 = (CS_7 + D_8)$
September	P_9	E_9	TE_9	$D_9 = (E_9 - TE_9)$	$CS_9 = (CS_8 + D_9)$
October	P10	E10	TE_{10}	D10 = (E10 – TE10)	CS10 = (CS9 + D10)
November	P11	E11	TE_{11}	D11 = (E11 – TE11)	CS11=(CS10 + D11)
December	P12	E12	TE_{12}	D12 = (E12 – TE12)	CS12 = (CS11 + D12)
Final total	$\sum CS_i$				

$E = a + b*P_i$ ……………………………………… ……………………………(1)

The energy equation, a linear relationship between energy consumption (E) and material production (Pi).

E: energy consumption, typically measured in kilowatt-hours (kWh).

Pi: material production amount, usually measured in tons (t)

a: intercept or the shift in the horizontal axis. It represents the baseline energy consumption when the material production amount is zero.

b: slope of the line, indicating the rate at which energy consumption changes with respect to material production amount.

By fitting the data of energy consumption and material production, the constants a and b can be determined through methods like the recursive least squares (RLS) method or other regression techniques. These constants capture the relationship between energy consumption and material production, allowing for the estimation of energy consumption based on the given material production amount.

The resulting line in the energy equation (E = a + b*Pi) can be plotted on a graph, where the energy consumption (E) is on the vertical axis and the material production amount (Pi) is on the horizontal axis. The slope (b) represents the steepness of the line, while the intercept (a) determines where the line intersects the horizontal axis..

The calculation of the slope (b) in equation (1) is as follows:

$$b = \frac{n * \sum E_j P_i - (\sum P_i)(\sum E_j)}{n * \sum P_i^2 - (\sum P_i)^2} \quad \text{……………………………………………..(2)}$$

a is a slide value on the horizontal axis. The calculation slide in the horizontal axis is as follows in Eq. (3);

$$a = \frac{\sum E_j - b*\sum P_i}{n} \quad \text{……………………………………………..(3)}$$

This analysis is important for defining a significant relationship between two variables. Therefore, a base line standard performance equation can be established using in regression analysis to measure the subsequent energy consumption for the CUSUM technique. The last four years of energy consumption and material production data were taken from Production department of NCSC plant.

Establishing the Energy Performance Model

There are several methods for establishing a model to understand the energy system and identify opportunities for efficiency improvement. The three methods you mentioned are commonly used:

• **Previous year's data**—simply using last year as a predictor of this year's consumption this is typically only useful when there are no significant factors of influence.

• **Regression analysis**—a statistical approach based upon historical consumption and the factors of influence.

• **Simulation model**—using complex numerical computer models to simulate the energy consumption

Regression analysis is commonly used to establish energy performance models, especially for basic systems. Linear regression, widely applied method for relating energy consumption to a single independent variable, such as degree-days or production, by regressing energy consumption against production output, possible to determine the energy intensity or energy consumption per unit of production. This allows for benchmarking against industry standards, identifying energy efficiency opportunities, and optimizing energy use in relation to production volumes.

Defining the Baseline

Defining a baseline period is an important step in energy performance analysis as it provides a reference point for comparing and evaluating energy consumption patterns over time. While trial and error analysis or knowledge about plant operations can be used to determine the baseline, additional techniques such as the CUSUM graph can help refine and redefine the baseline period.

CUSUM (Cumulative Sum) analysis is a statistical method that can be used to detect changes or shifts in energy performance over time. It involves plotting the cumulative sum of the differences between actual energy consumption and the expected energy consumption based on the baseline period.

- Downward Trend: A downward trending line indicates energy savings or improved energy performance compared to the baseline. It suggests that measures or actions taken have resulted in reduced energy consumption or improved efficiency.
- Upward Trend: An upward trending line indicates a higher rate of consumption or deteriorating energy performance compared to the baseline. This suggests that there may be inefficiencies or changes in operations that have led to increased energy consumption.

By utilizing the CUSUM graph, energy managers can identify deviations from the baseline, track the effectiveness of energy-saving measures, and make informed decisions to improve energy performance.

Setting Performance Targets

The strategies for setting targets include:

Eliminating the highest or least efficient points from the data set:

Defining best historical performance as the target:

Controlling performance

Once a target has been set, the challenge is to manage performance to achieve and sustain that performance. Control charts, similar to those used in statistical process control, can be a valuable tool for monitoring and controlling energy performance.

4.2.3. Performance assessment of process units

4.2.3.1. Raw Mill

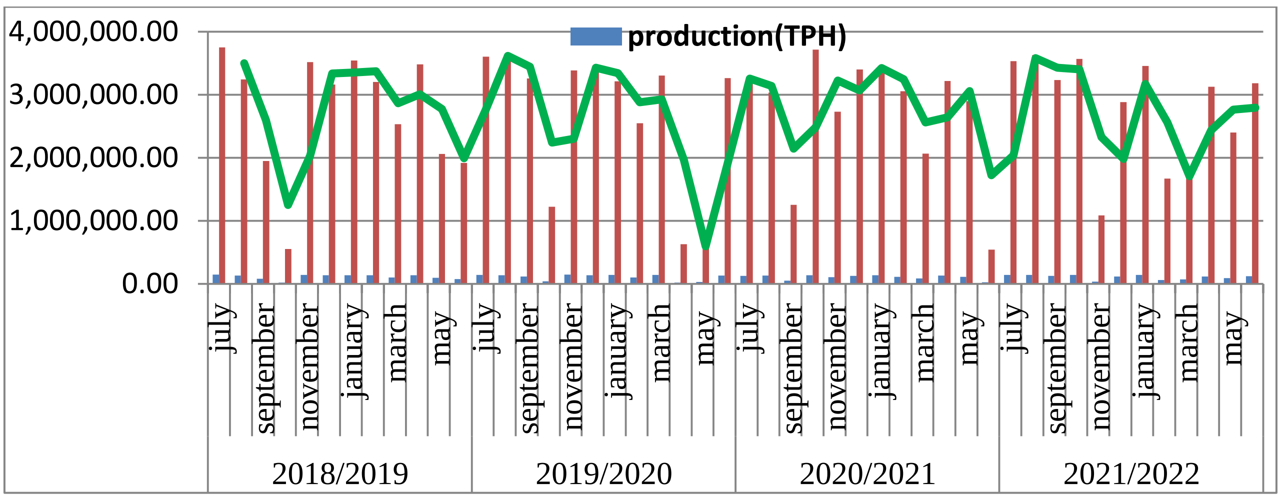

Figure 4.7: Monthly raw meal production with energy consumption data

The production rated capacity of the raw mill is 6240 tons per day (TPD), while the average production rate calculated from the four years of data assessment is 4128 TPD. This means that the raw mill is operating at a production performance or load of 66% (4128 TPD divided by 6240 TPD).

To improve the production performance of the raw mill, several factors can be considered, such as optimizing raw material quality and consistency, ensuring efficient operation and maintenance of the mill, and implementing process control measures to maximize production output.

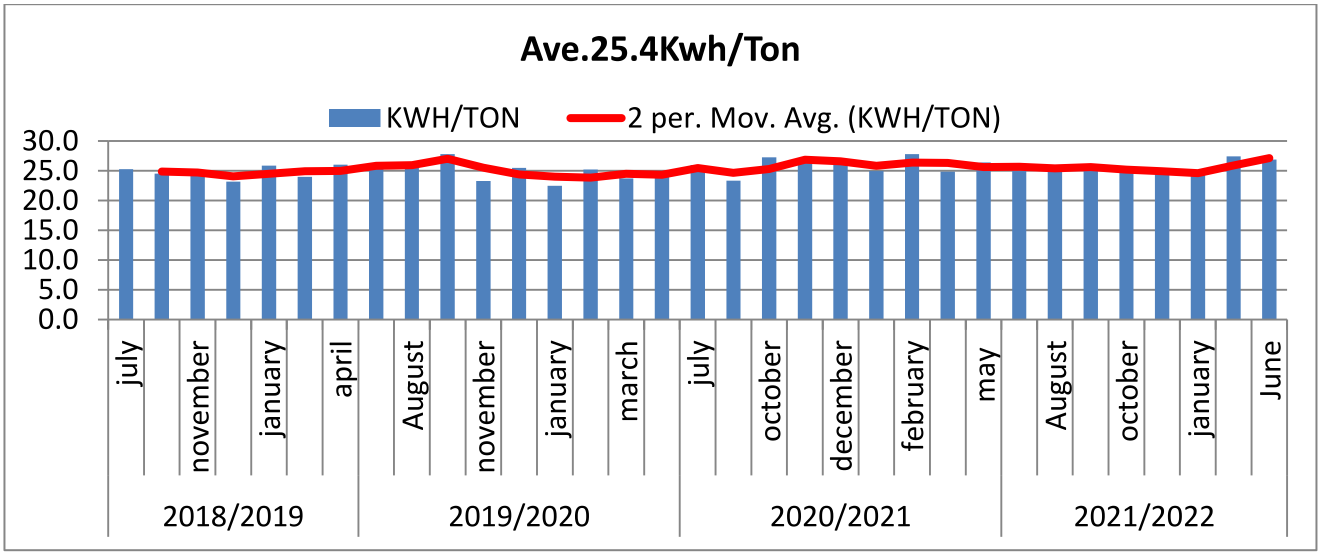

Figure 4.8: Raw mill specific energy consumption

The raw mill exhibits an average specific energy consumption 25.4 kWh/ton, which matches the rated design of specific energy consumption. The rated capacity of the raw mill is typically determined by factors such as the size and design of the mill, the capacity of the motor driving the mill, and other operational considerations. This capacity represents the maximum production output that the raw mill is designed to achieve under ideal conditions. On the other hand, the production performance or load, which in this case is 66% of the rated capacity, indicates the actual production output relative to the maximum capacity. The production performance can be influenced by various factors, such as operational efficiency, maintenance practices, material characteristics, and process control.

The specific energy consumption, which is the energy required to produce one ton of raw material, does not directly determine the production capacity. It represents the energy efficiency of the mill in converting energy input into output. It is possible for a mill to have high specific energy consumption but still operate at its rated capacity, or vice versa.

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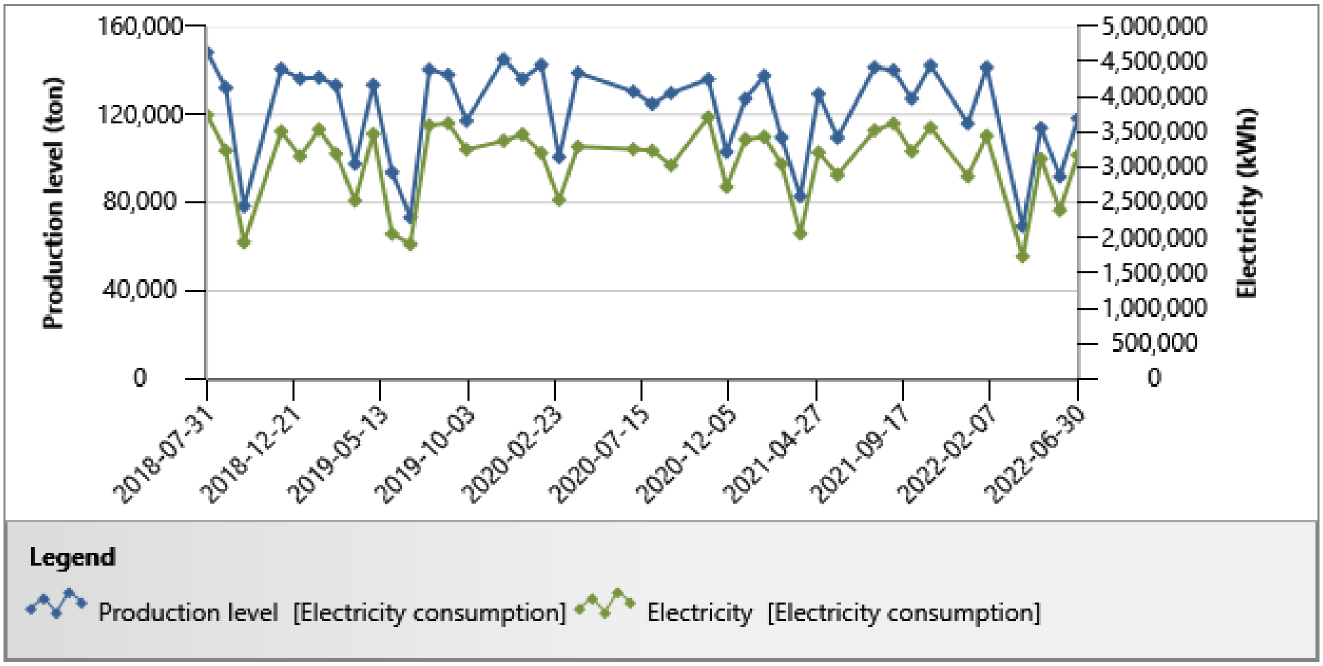

Figure 4.9: Time series data of production with electric energy consumption of the raw mill

There is significant gap between the production and energy consumption as shown in this time series the values for the two parameters is visibly illustrates the energy consumption is very high compared to its production performance. This is shown again with specific energy consumption and CUSUM both indicate that the energy consumption per ton of clinker is higher after mid of 2020 and significant attention should be given to the raw mill

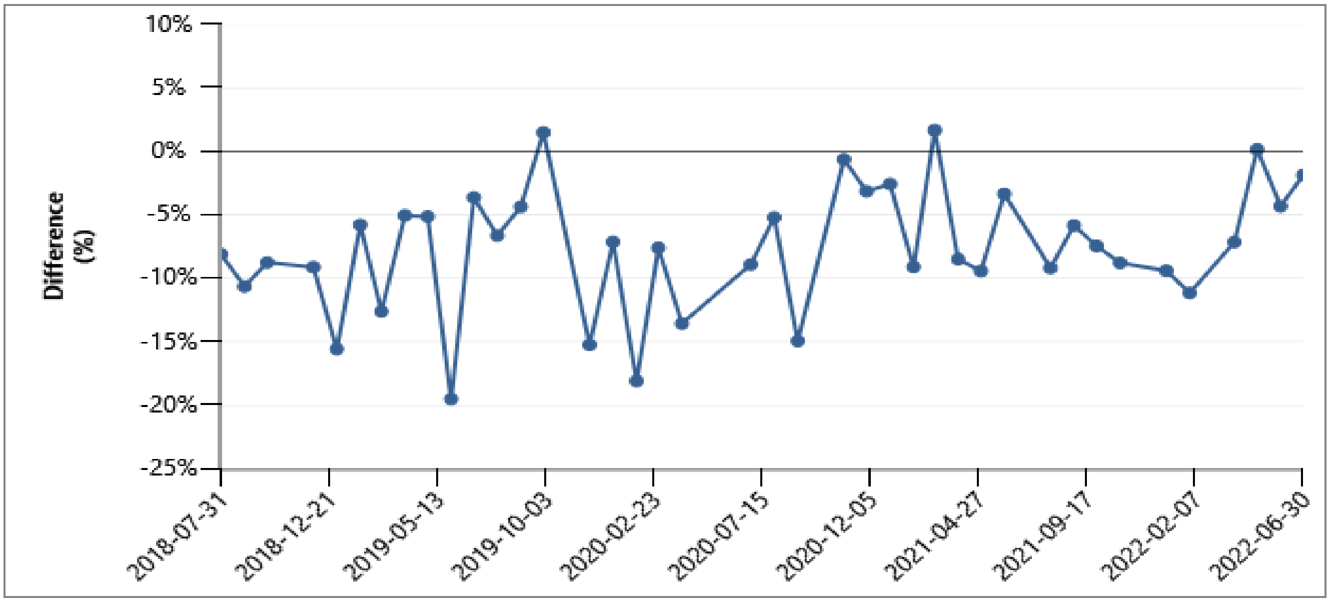

Figure 4.10: Control charts of the raw mill

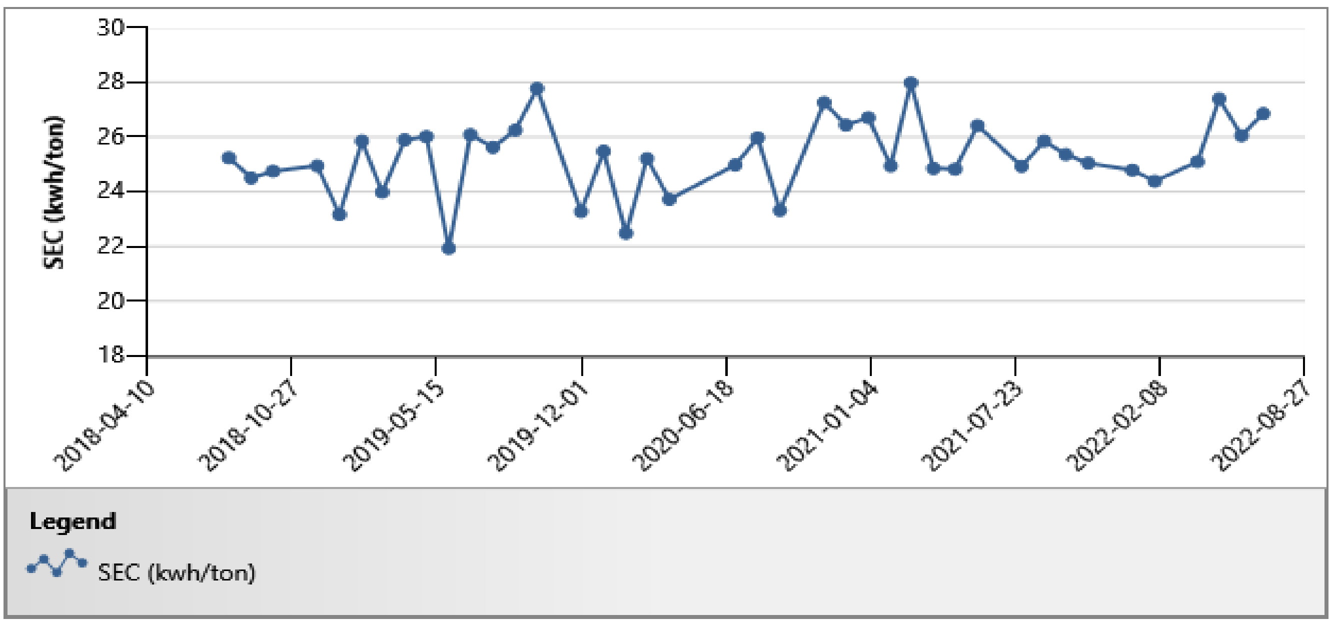

Figure 4.11: Specific energy consumption (kwh/ton)

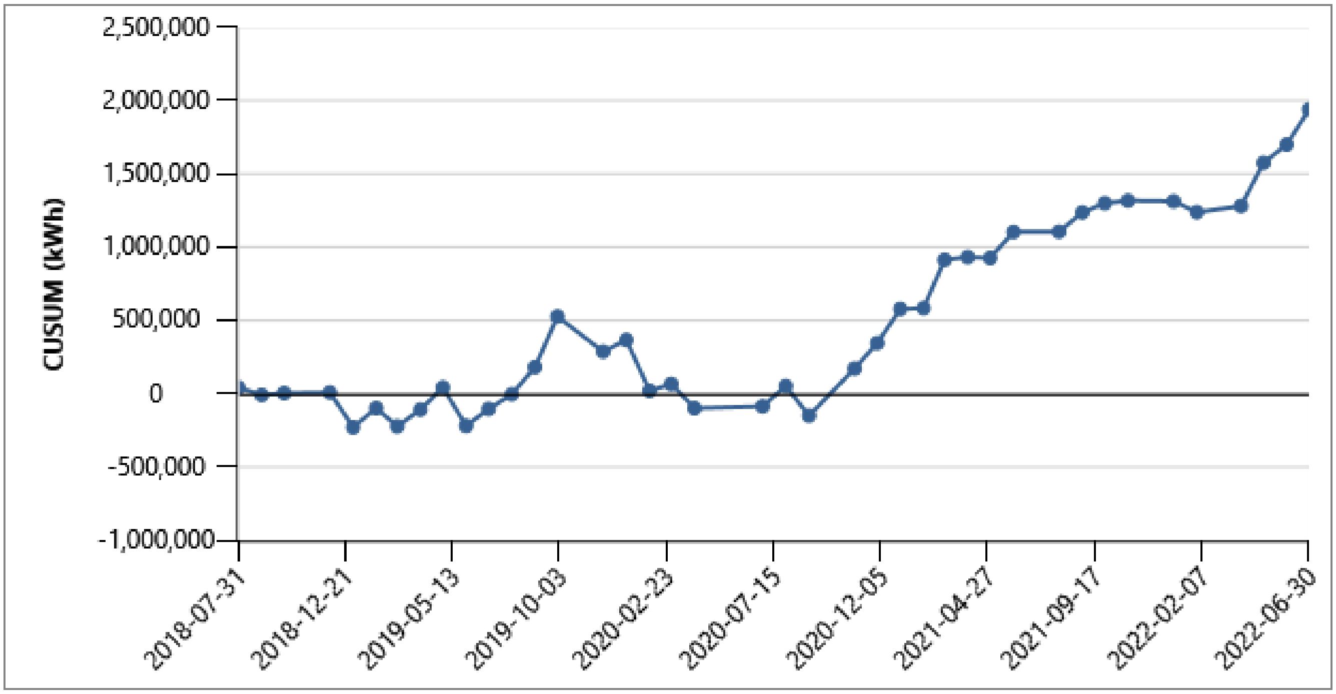

Figure 4.12: CUSUM plot of the raw mill

The specific energy consumption is consistently increasing or deviating above the expected or target value after mid of 2020. This suggests that the raw mill is experiencing higher energy consumption over time. Positive deviations in the CUSUM graph indicate a need for closer monitoring and potential investigation into the factors causing increased energy consumption. It may indicate issues such as equipment degradation, changes in process conditions, or other inefficiencies that require attention to optimize energy usage

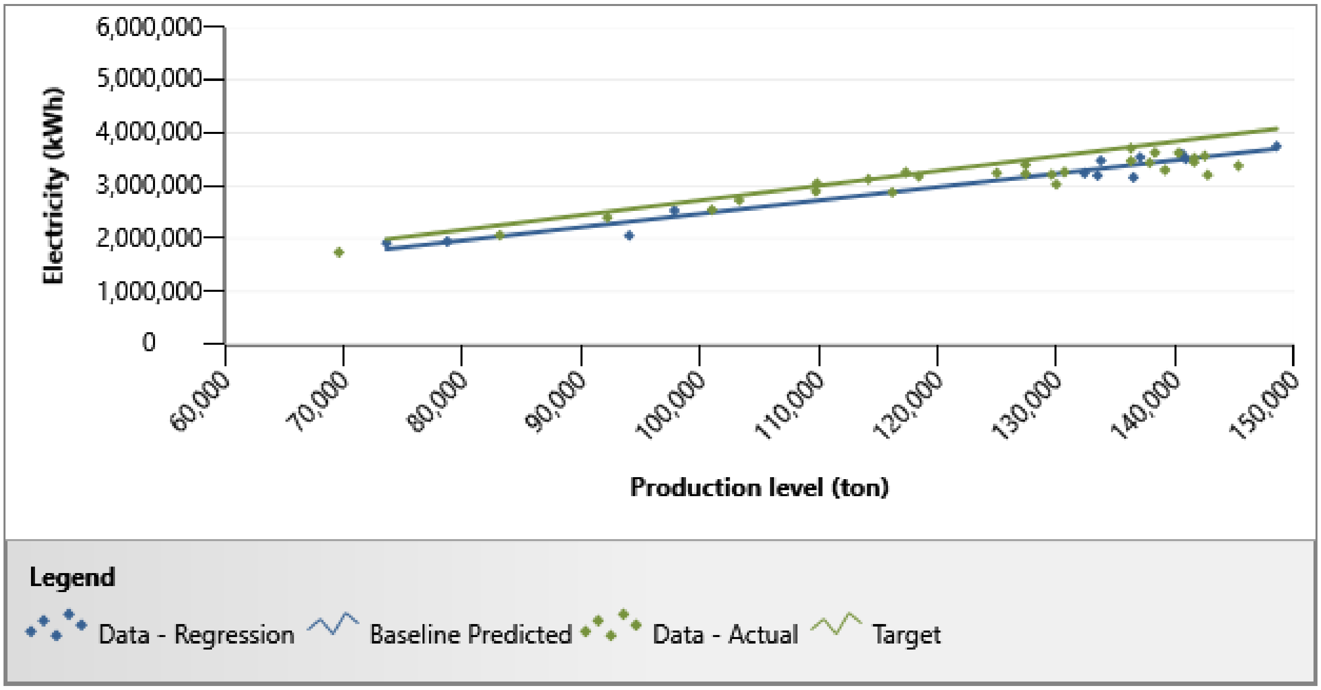

Figure 4.13: Target energy consumption set

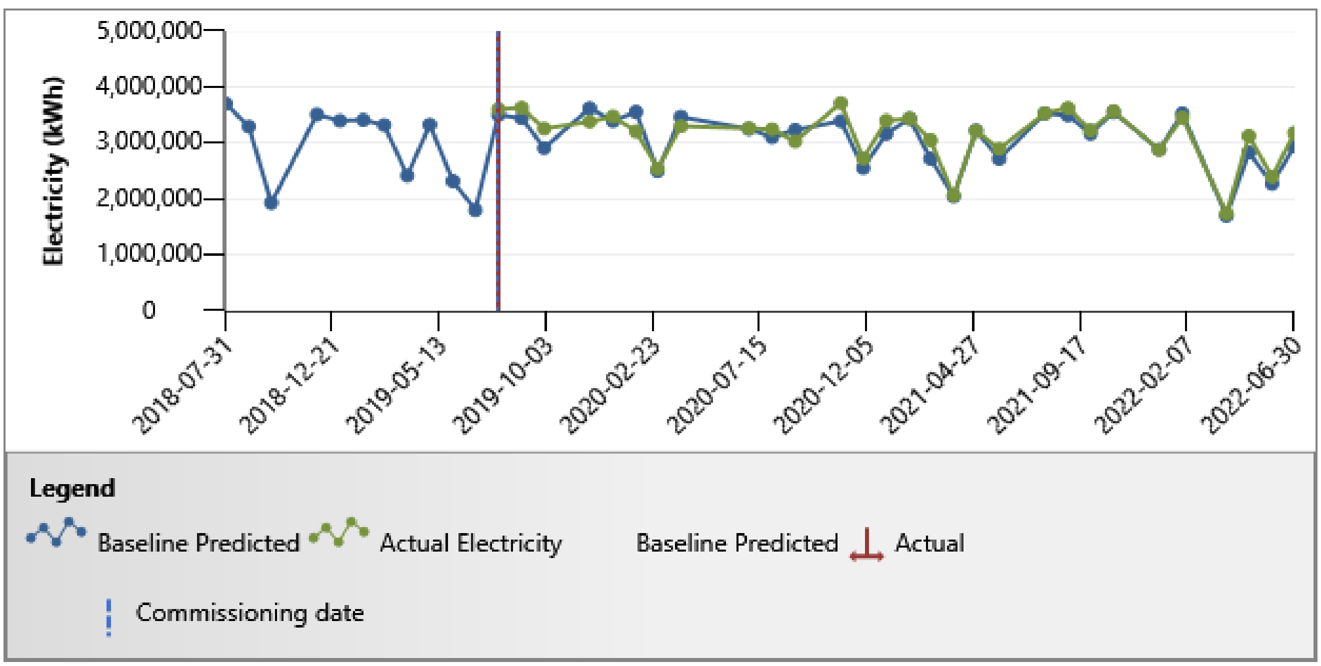

Figure 4.14: Figure 4.16: Target energy saving from the raw mill

The net savings as of June 30, 2022, from the raw mill's energy consumption is -1,943,362 kilowatt-hours (kWh). The value indicates that the raw mill is consuming more energy than expected or desired.

It suggests that there is room for improvement in terms of energy efficiency and reducing energy consumption.

A downward trending line indicates energy saved in comparison to the baseline performance, while an upward trending line indicates a higher rate of consumption. The baseline for the first 12 months gives an energy model of the following (Taner, T., Sivrioğlu, M., Topal, H., Dalkılıç, A. S., & Wongwises, S. , 2018)

E = 25.35 P – 58,366.5

Where E is energy consumption while P is production

Target Saving

The CUSUM graph indicates when performance changes occurred, and what they achieved in terms of energy saved or wasted. It does not directly indicate how or why those changes occurred.

In this audit assessment 10% saving of the production related and non-production related is targeted accordingly the above equation will be modified to the target energy

Performance model equation

E = 22.82 P – 52,530

Controlling the Raw Mill Performance

Once a target has been set, the challenge is to manage performance to achieve and sustain that performance. Control charts similar to those used to manage other functions can be constructed from the energy monitoring analysis to control energy performance.

A new set of predicted energy consumption values can be calculated, the “target” consumption as shown in figure 4.13 and 4.14 the variance between actual and target consumption is then calculated; positive values indicate consumption above target, negative below

4.2.3.2. Coal Mill performance assessment

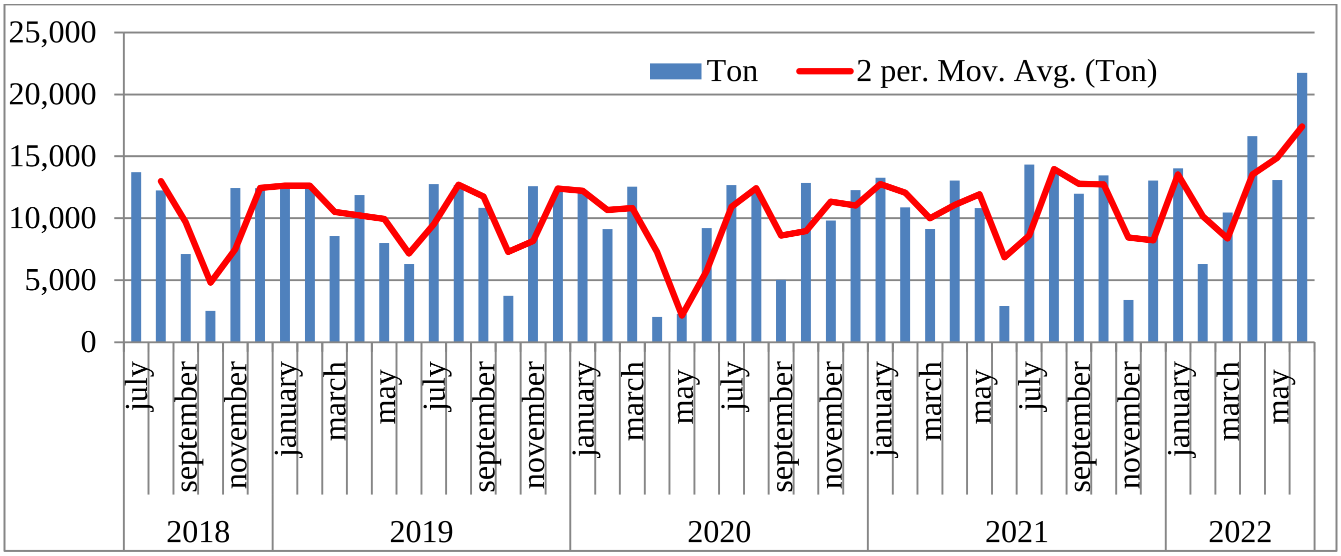

Figure 4.15: Production performance of coal mill

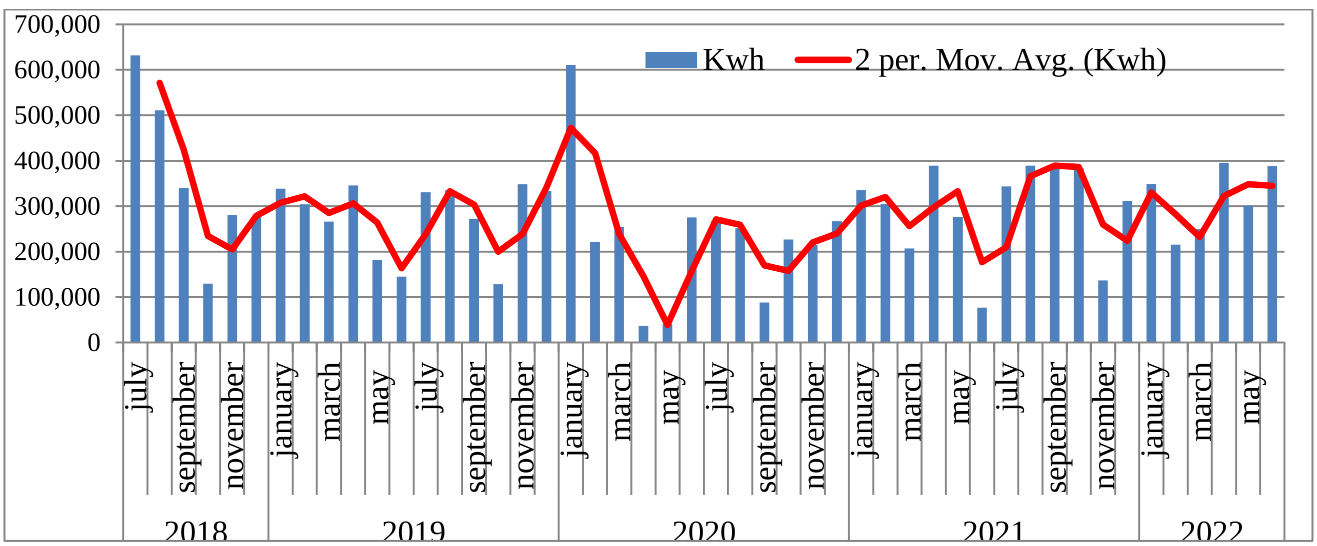

Figure 4.16: Energy consumption of coal mill

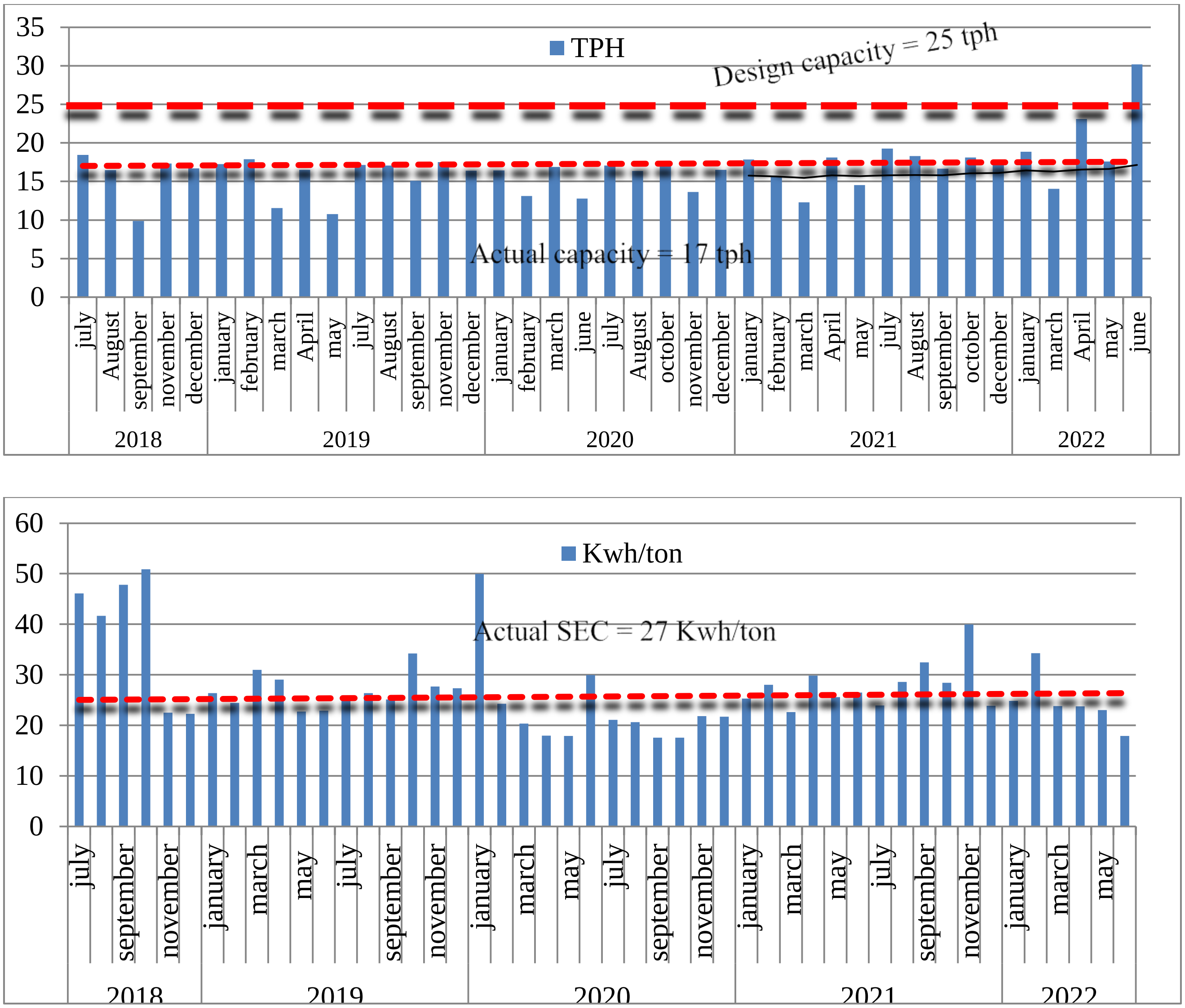

Figure 4.17: Coal mill design capacity Vs. actual capacity

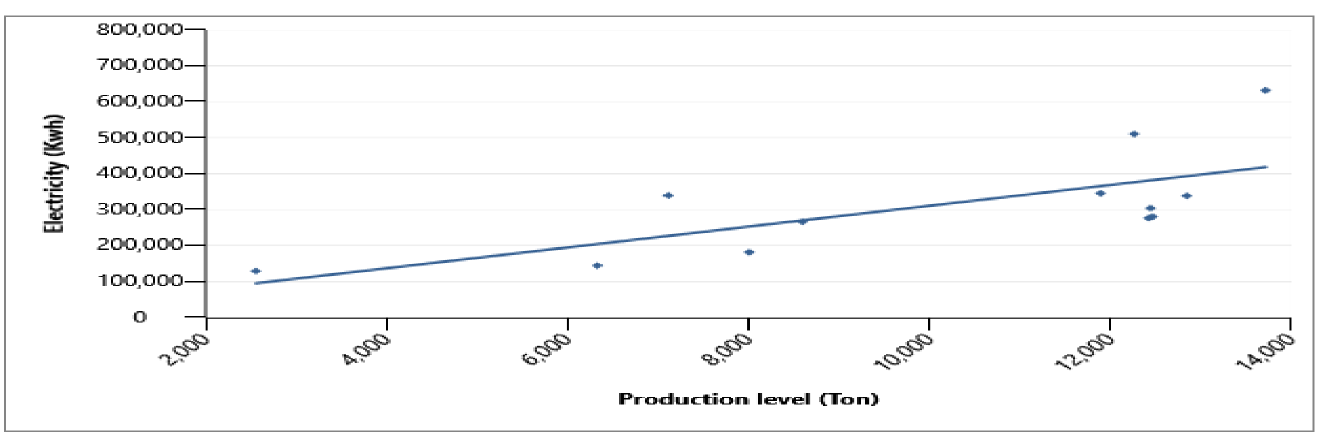

Figure 4.18: Figure 4.18 shows the Coal mill performance; baseline energy performance model for the first 12moths is found as

$E = 27.83P + 28,455.4$

Where E is energy consumption while P is production

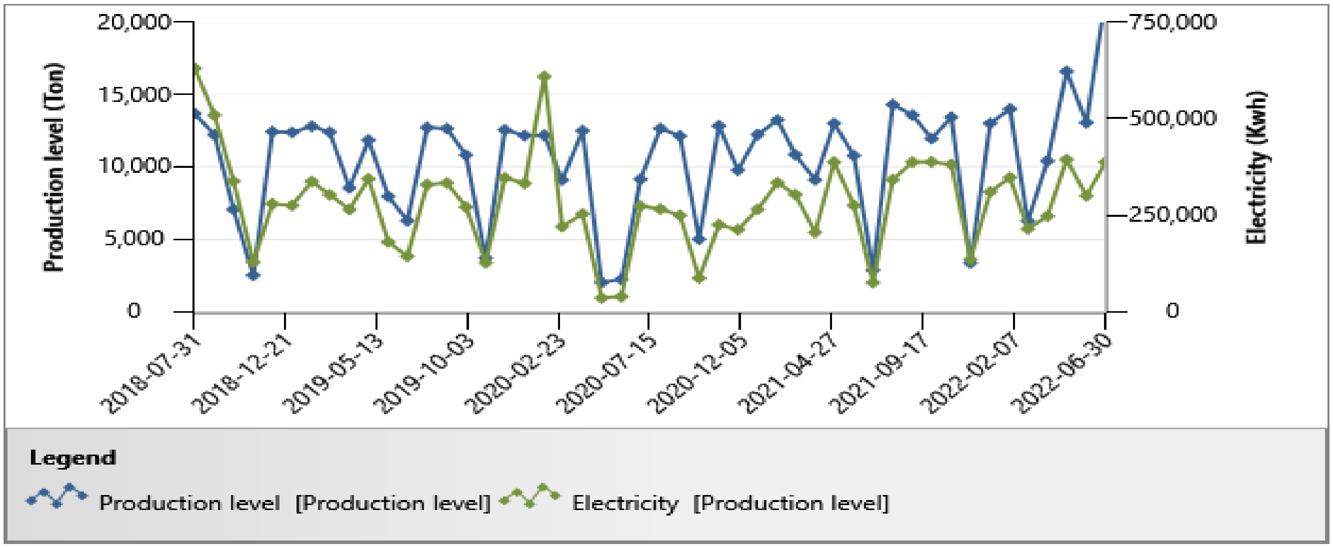

Figure 4.19: Time series of production and electrical energy consumption of coal mill

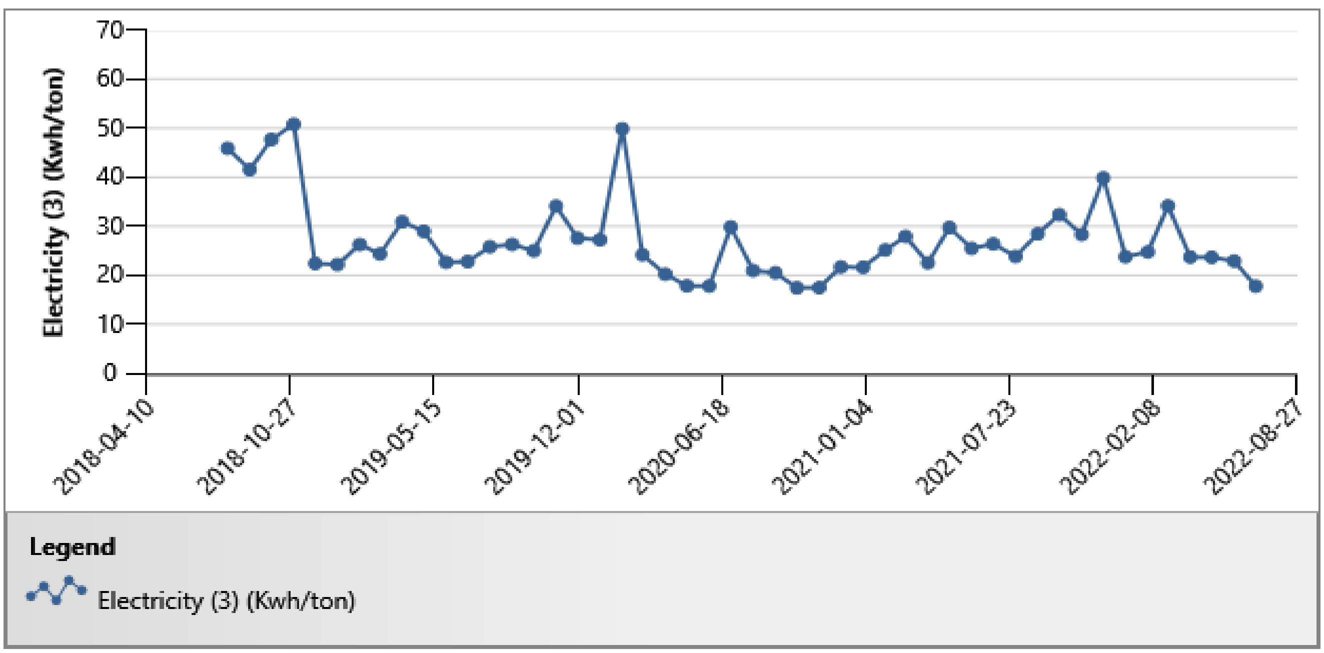

Figure 4.20: Specific energy consumption of the coal mill

The energy consumption of the coal mill has remained relatively consistent over the past couple of years, as indicated in the figure 4.23; it suggests that the coal mill has been operating at a relatively stable energy consumption level during the period.

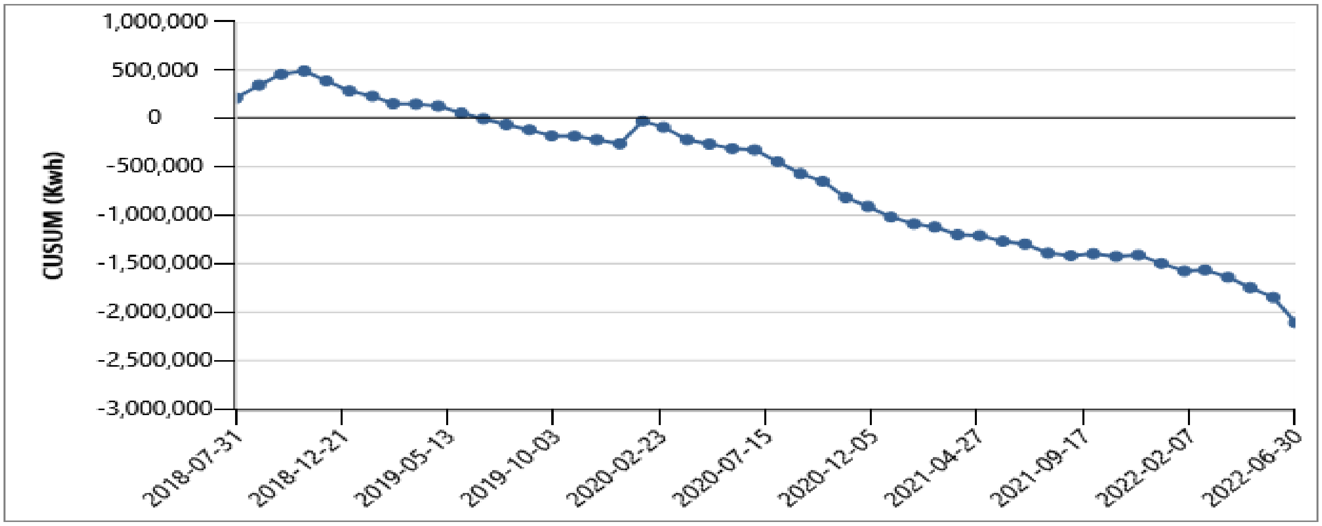

Figure 4.21: CUSUM of the Coal Mill

The Cumulative Sum (CUSUM) of differences can be used as an indicator of potential net energy savings when compared against the best performing duration of a coal mill. The CUSUM involves calculating the difference between the actual and predicted values for each period and then adding them together to create a running total or cumulative sum. This cumulative sum represents the cumulative savings achieved or the cumulative deviation from the optimal or predicted energy consumption of the coal mill. Positive values of the CUSUM indicate that the actual energy consumption is lower than the predicted or optimal values, indicating potential energy savings. Conversely, negative values indicate that the actual energy consumption exceeds the predicted values, suggesting potential inefficiencies or energy losses.

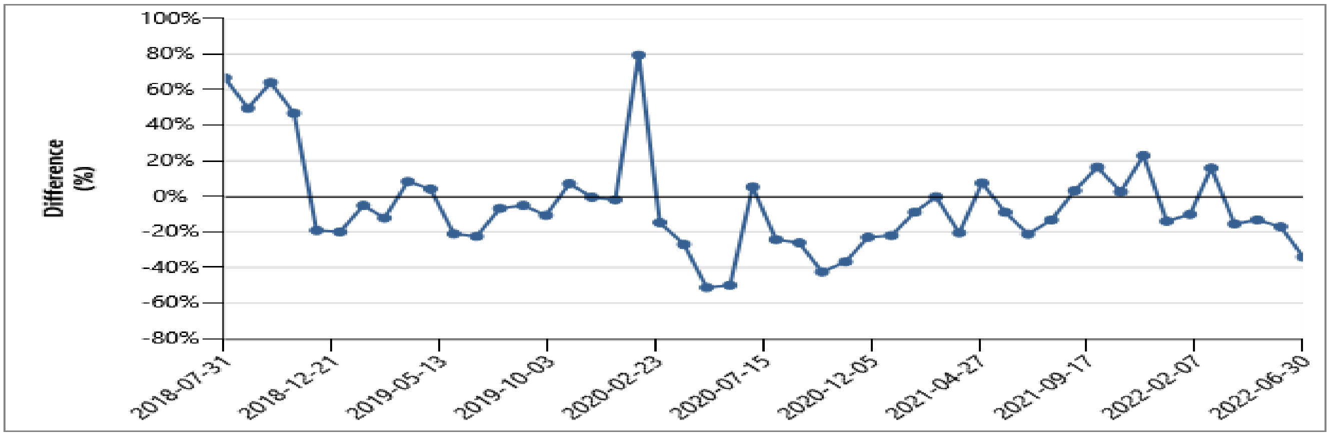

Figure 4.22: Control chart of the Coal Mill

Control charts are graphical tools used to track and monitor the performance of a process over time. By monitoring the control chart, shop floor operators can observe the performance data points and assess whether the coal mill's actual performance stays within acceptable limits or deviates significantly. If the data points consistently trend below 0%, it indicates that the coal mill is performing better than the targeted performance, potentially resulting in energy savings.

The Control charts for tracking actual performance of the coal mill in comparison with the targeted performance. As shown in figure 4.22, following the control chart trend below 0% will benefit more for shop floor operators

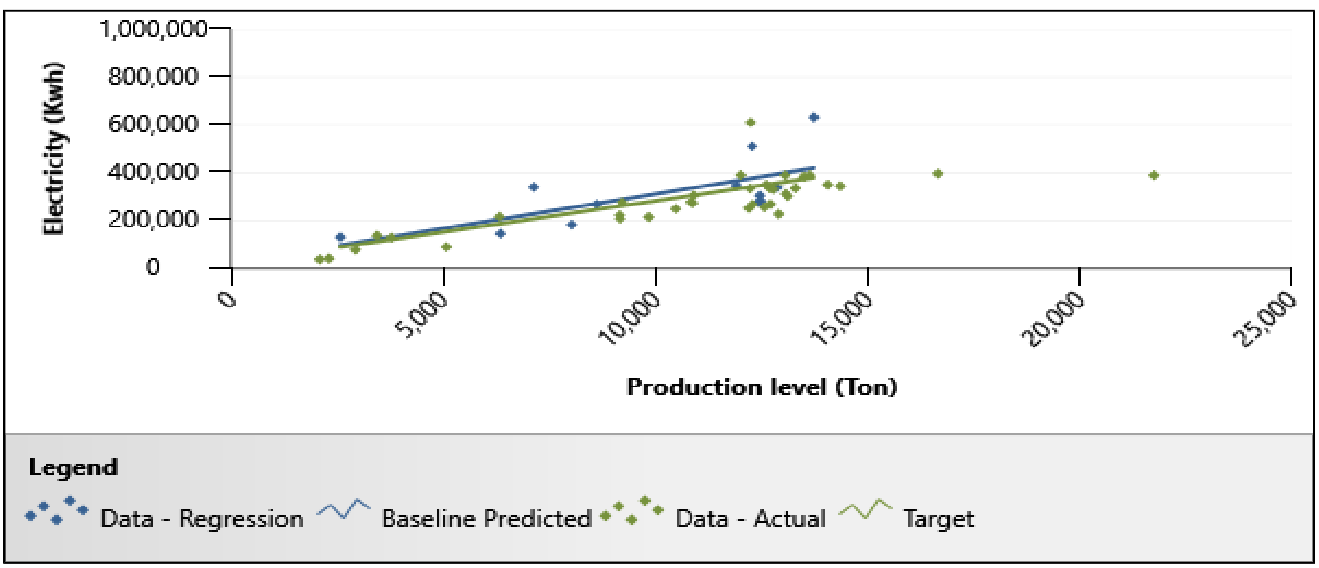

Figure 4.23:Target energy consumption set of Coal Mill

The target saving against the best performance period of the coal mill is 10%. Additionally, a 10% target saving corresponds to an equivalent percent improvement in the rate of energy consumption, excluding the non-production related base load. Therefore, the target energy performance model for the coal mill, in terms of the rate of energy consumption, can be expressed as:

$E = 25.05P + 25{,}610$

Where E is the energy consumption, P is the production output, and the values 25.05 and 25,610 are derived based on the specific characteristics and performance of the coal mill.

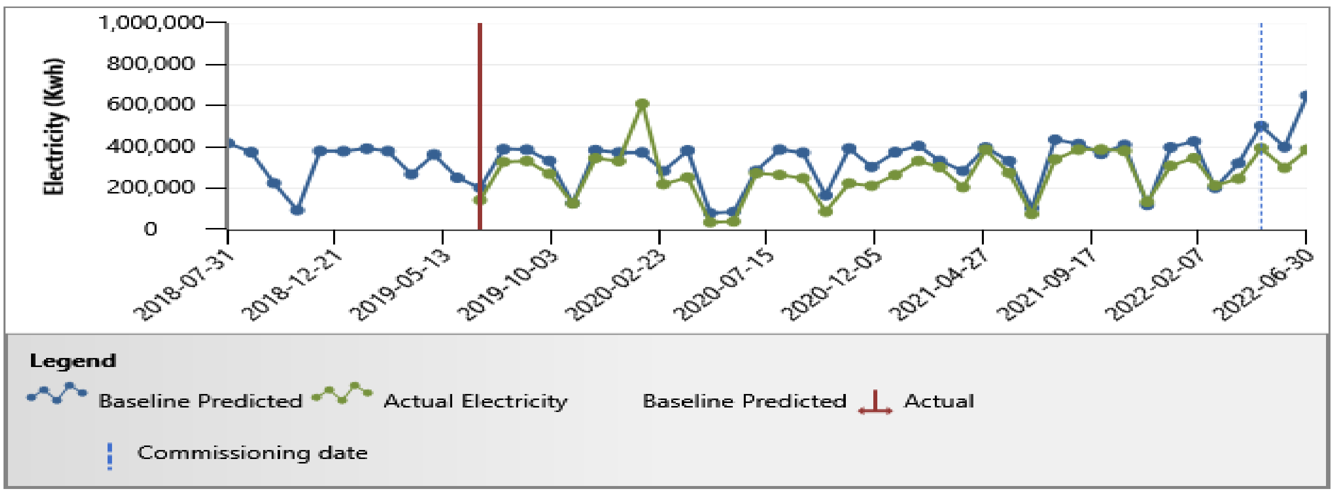

Figure 4.24: Measurement and verification of coal mill

Figure 4.17 shows the Energy consumption of coal mill, in the four years considered for this study the coal mil consumed 13,695,460.84 kWh of energy to ground 509,938 ton of coal, the production performance of coal is 68 % with actual production of coal per day at 408 TPD and the design production capacity 600TPD as shown in Figure4.18 Production performance of Coal Mill.

The production rate design capacity of the coal mill is 25TPH and the actual production rate found analyzing the data in the four years is 17 TPH as shown in Figure 4.19 The Specific energy consumption of the Coal mill as shown in Figure4.20 is 27 kWh/ton which is similar when compared with bench marks in the local as well as international best practicing cement plants.

The net saving from the measuring and verification chart indicates about **361,157kWh** is saved until June 2022

4.2.3.3. Kiln Performance assessment

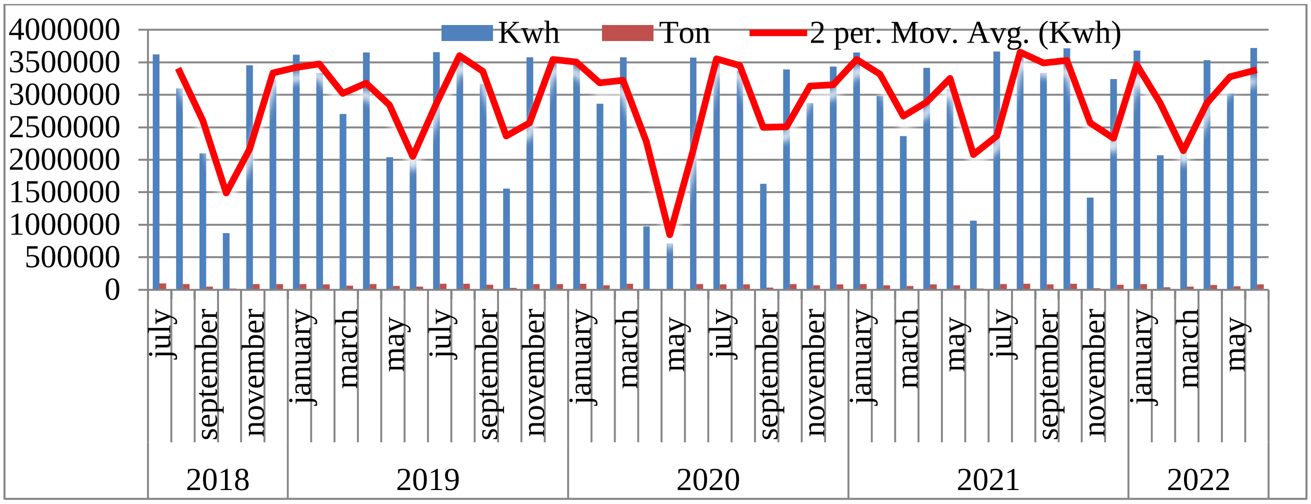

Figure 4.25: Monthly kiln production with consumption

The clinker production of the Kiln is 2640 TPD which is 88 % of its design production capacity 3000TPD.The production of the kiln is in the four years data assessment is about 3,331,087 ton of clinker.

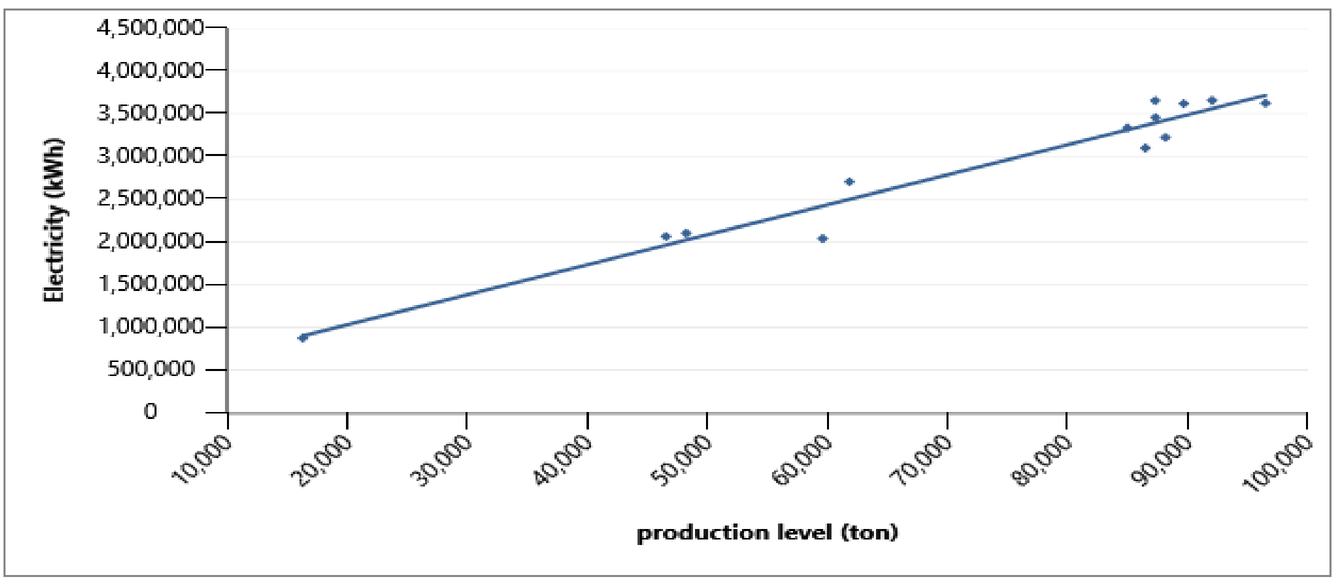

Figure 4.26: Baseline period of the kiln performance

The kiln performance history for the four years gives the target energy performance model is with R^2 = 0.95 as E = 35.08 P + 330,584.8. This energy model is depicted on the best performing periods of the kiln

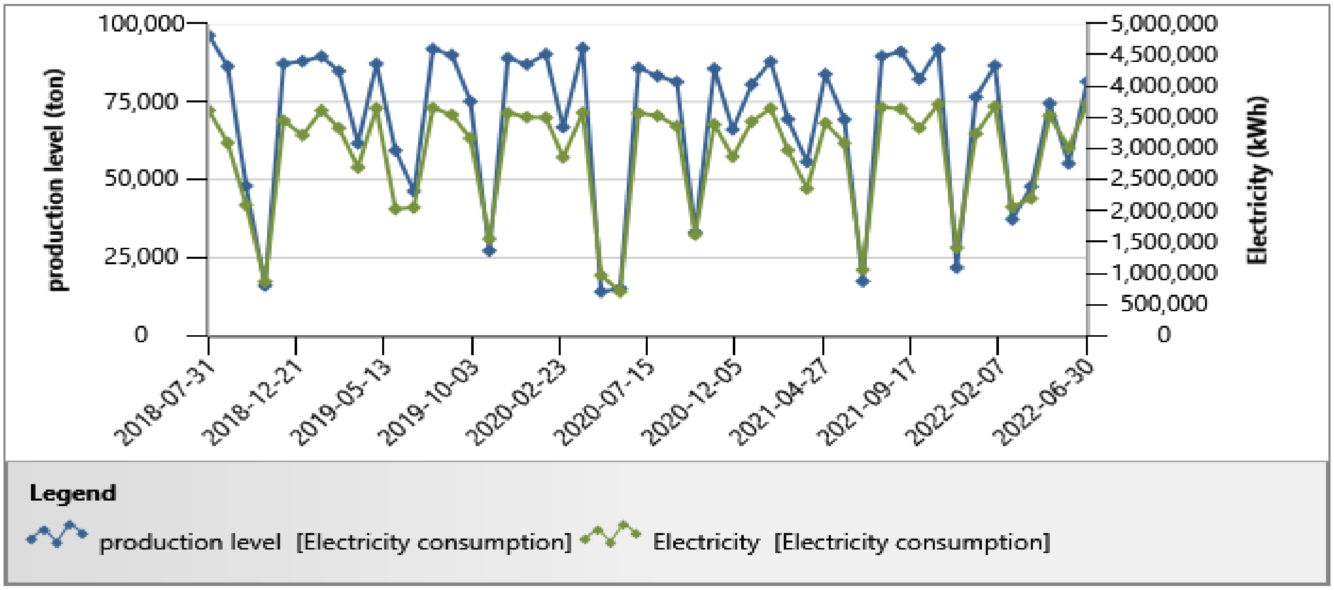

Figure 4.27: Time series plot of the production of clinker with energy consumption

From fig 4.27 there is a significant gap between the production and energy consumption in the time series of the kiln, with energy consumption being noticeably higher compared to production performance, it shows inefficiency in energy utilization. The net saving from the measuring and verification chart indicates about **-7,321,449 (kWh)**, is wasted until June 2022, this situation requires further investigation to identify the underlying causes and potential solutions.

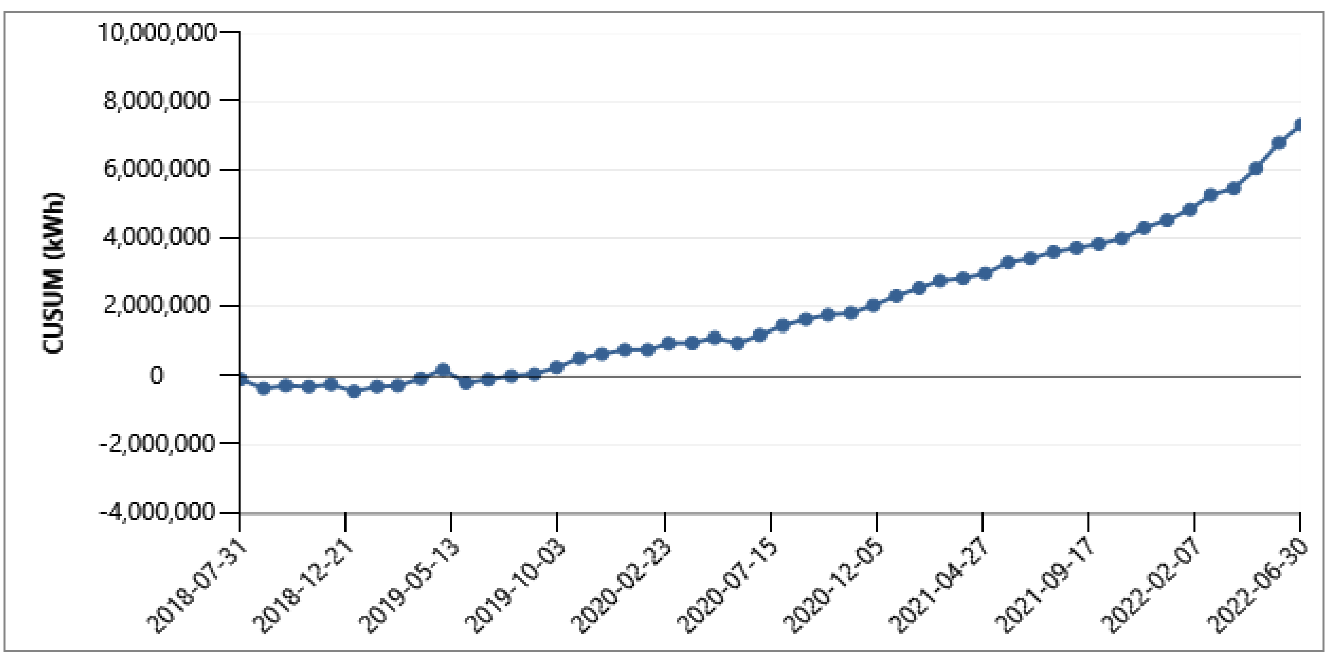

Figure 4.28: CUSUM of the kiln

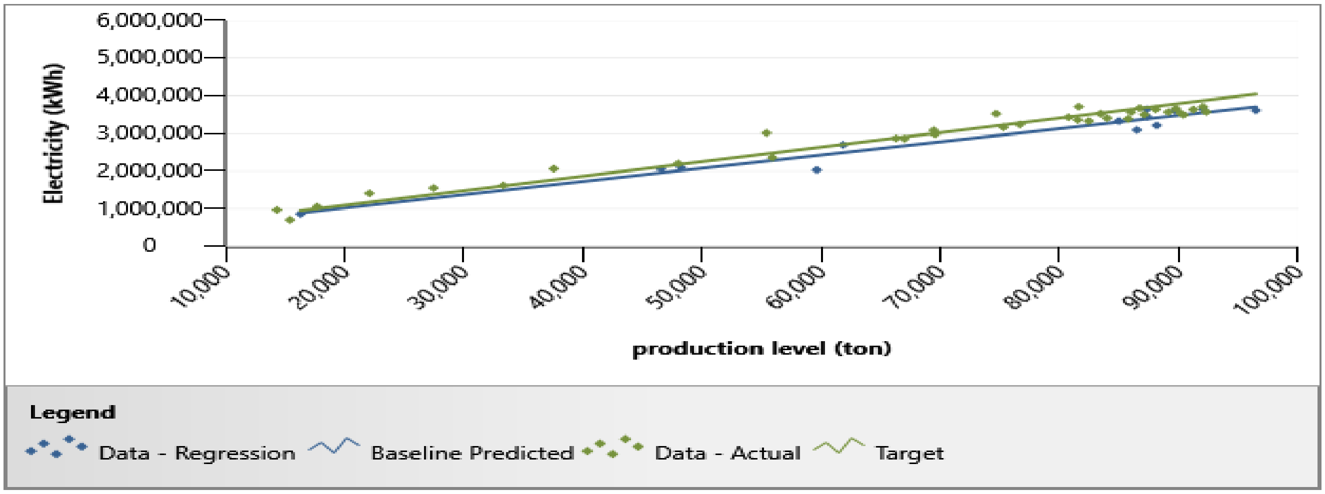

Figure 4.29: Control chart of the kiln

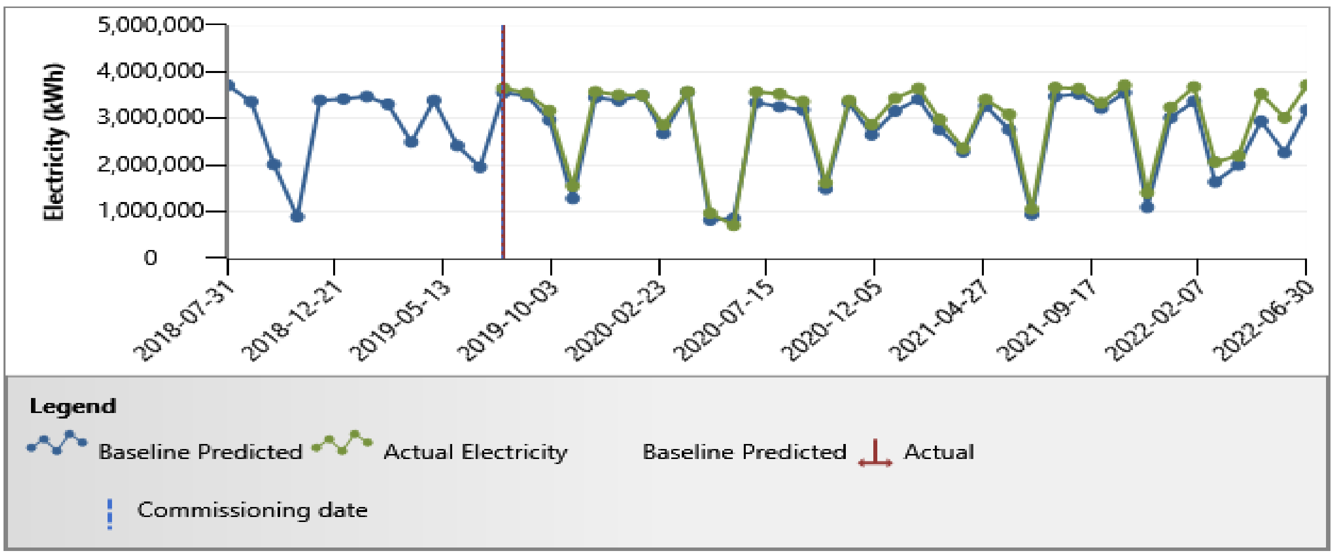

Figure 4.30: Measurement and Verification (Baseline) of the Kiln

4.2.3.4. Cement mill Performance assessment

Table 4.23: yearly production and energy consumptions data for Cement Mills from 2018/2019 – 2021/2022

Year	Production level (ton)	Electricity consumption (Kwh)
2018	500,431	25,908,573
2019	939,170	49,244,920
2020	1,104,152	54,024,150
2021	1,222,278	60,516,338
2022	573,699	29,684,354
Total	4,339,730	219,378,335

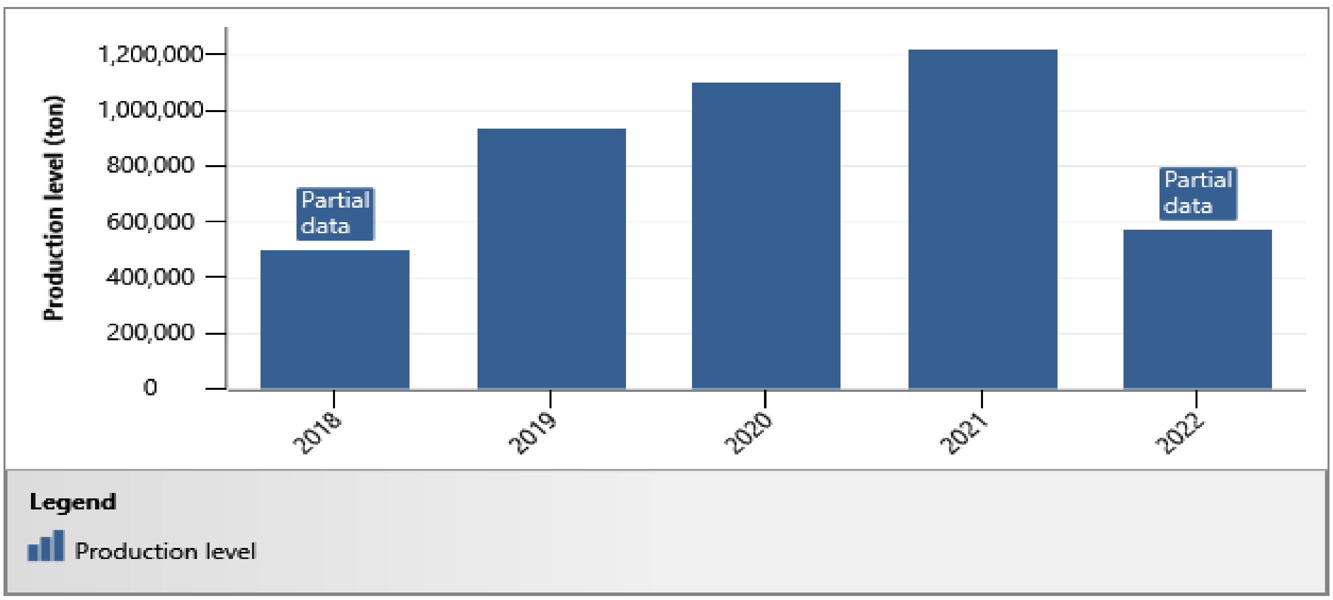

Figure 4.31: Annual data for production of cement mills (CM1&CM2)

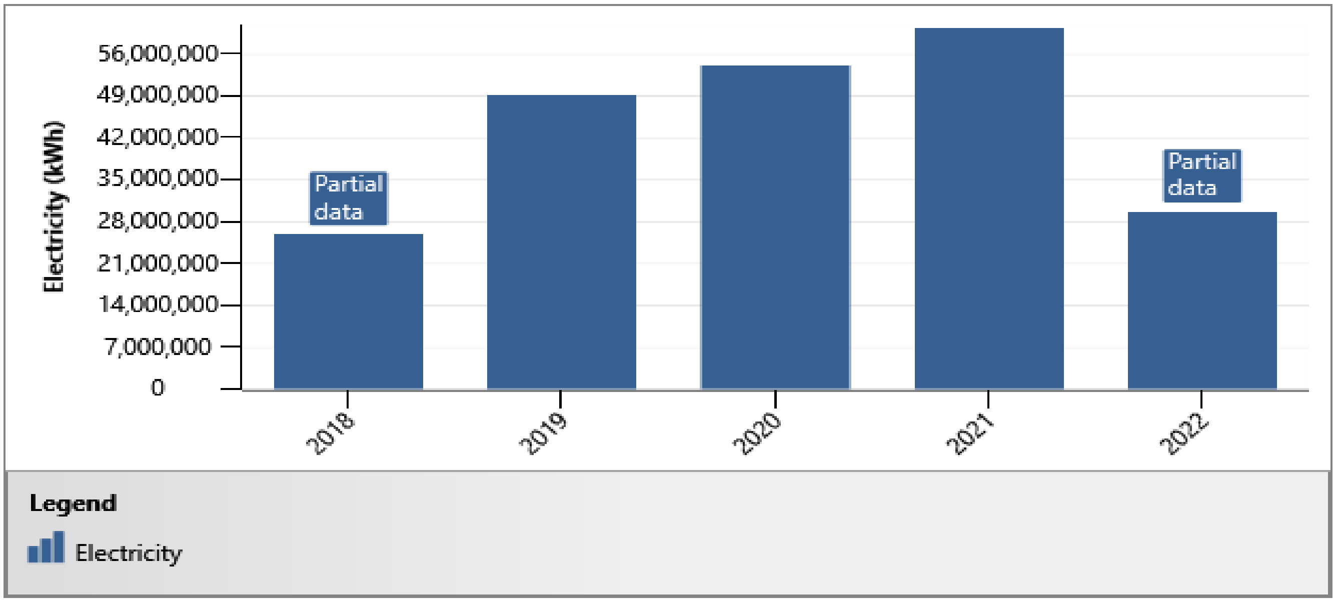

Figure 4.32: Annual data for electricity consumptions of cement mills (CM1&CM2)

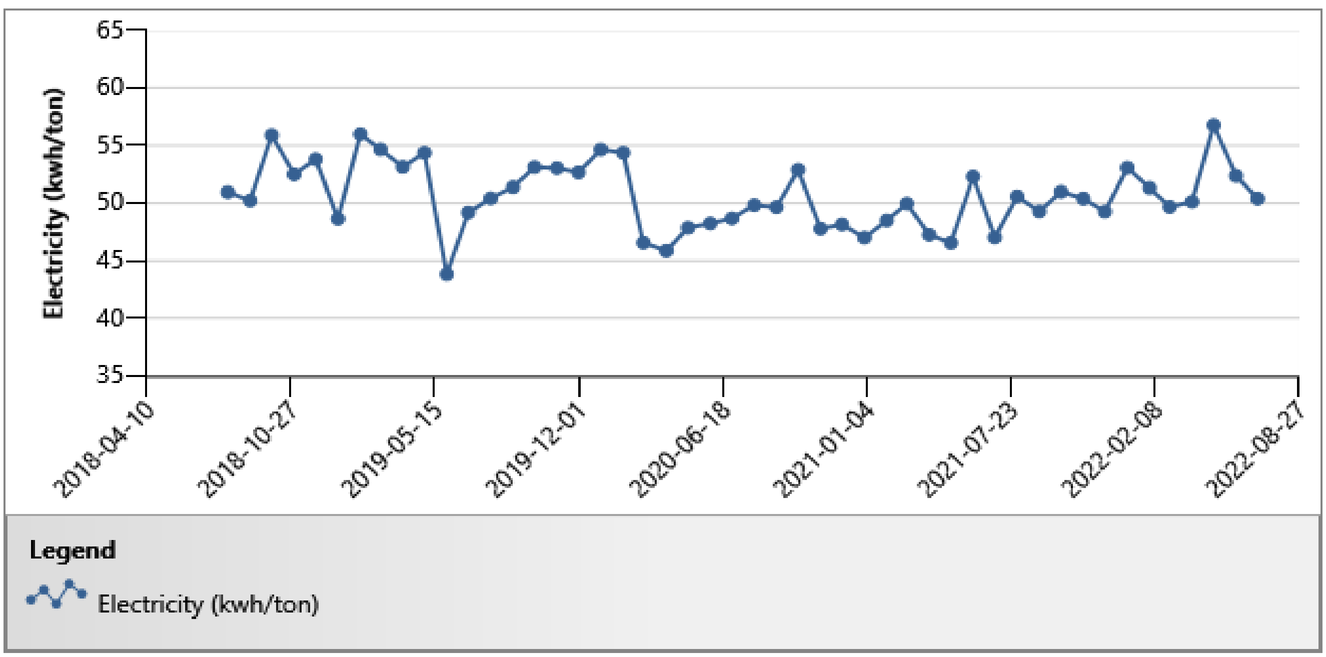

Figure 4.33: Specific energy consumption of the cement mills

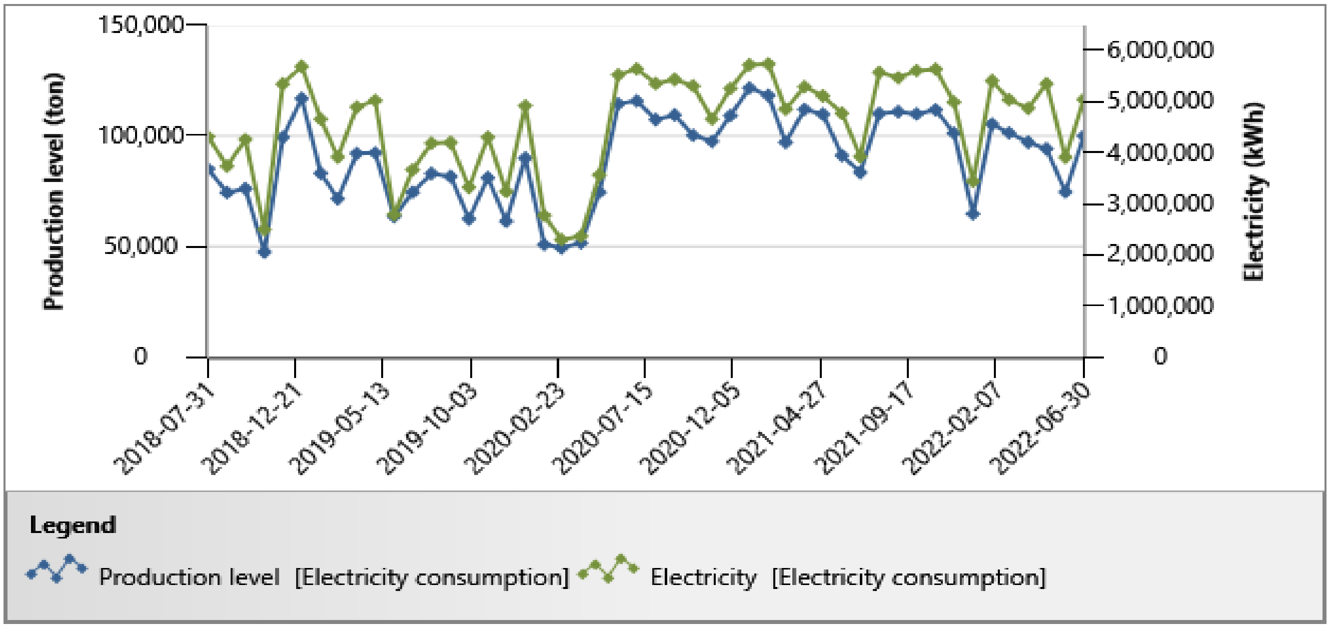

Figure 4.34: Time series plot of the production of cement mills with energy consumption

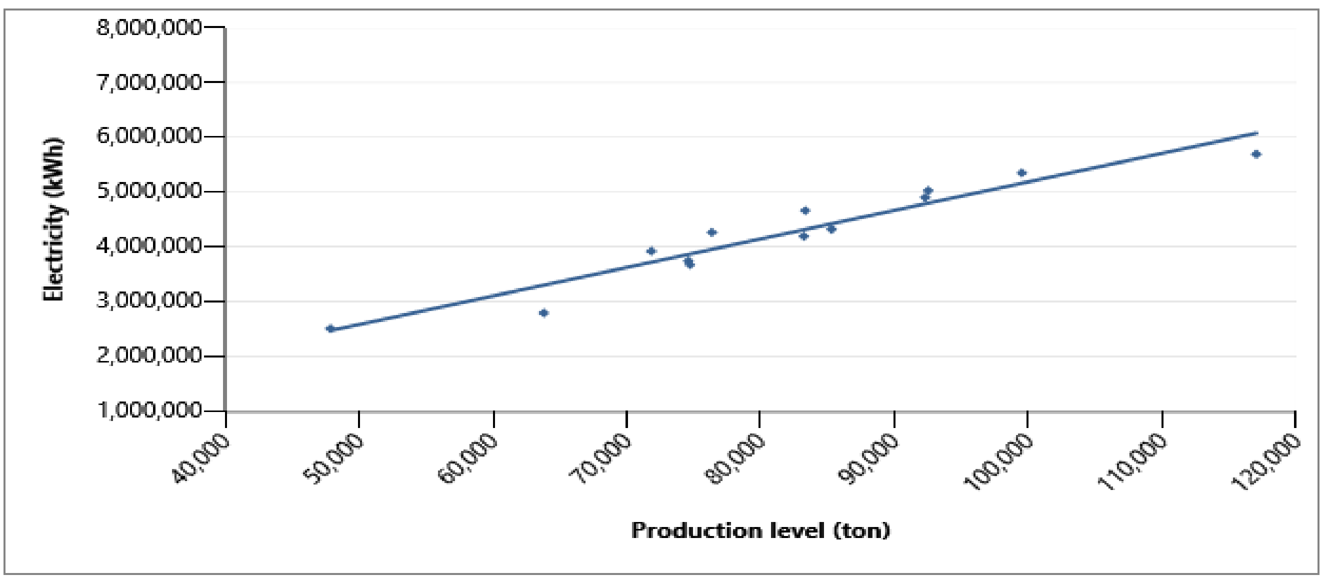

Figure 4.35: baseline plot

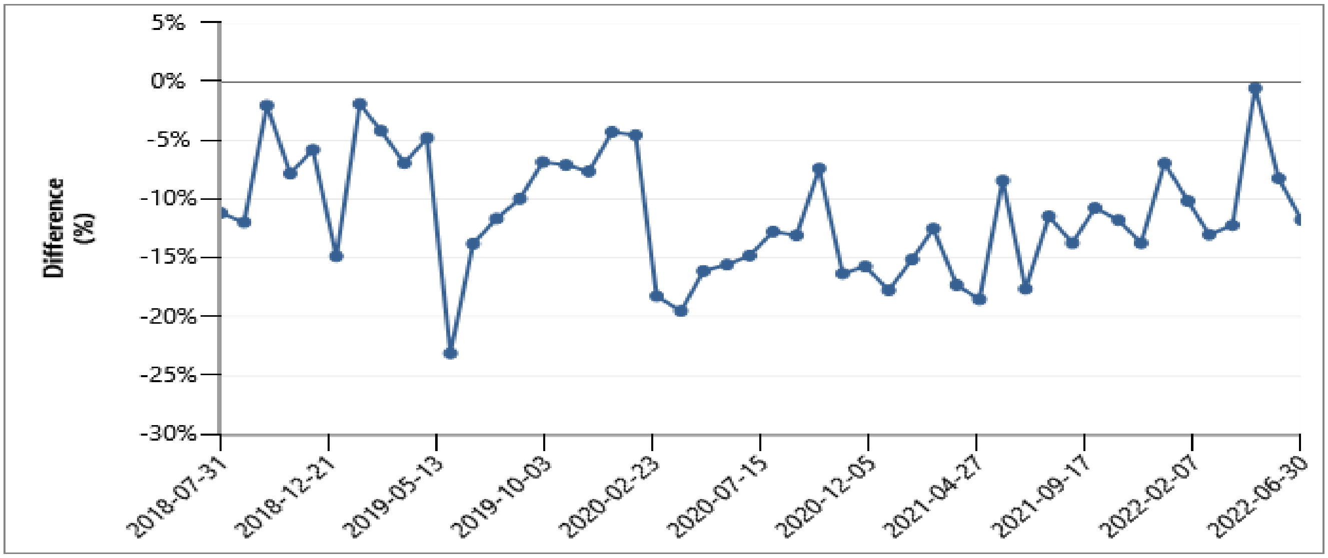

Figure 4.36: Control chart for cement mills

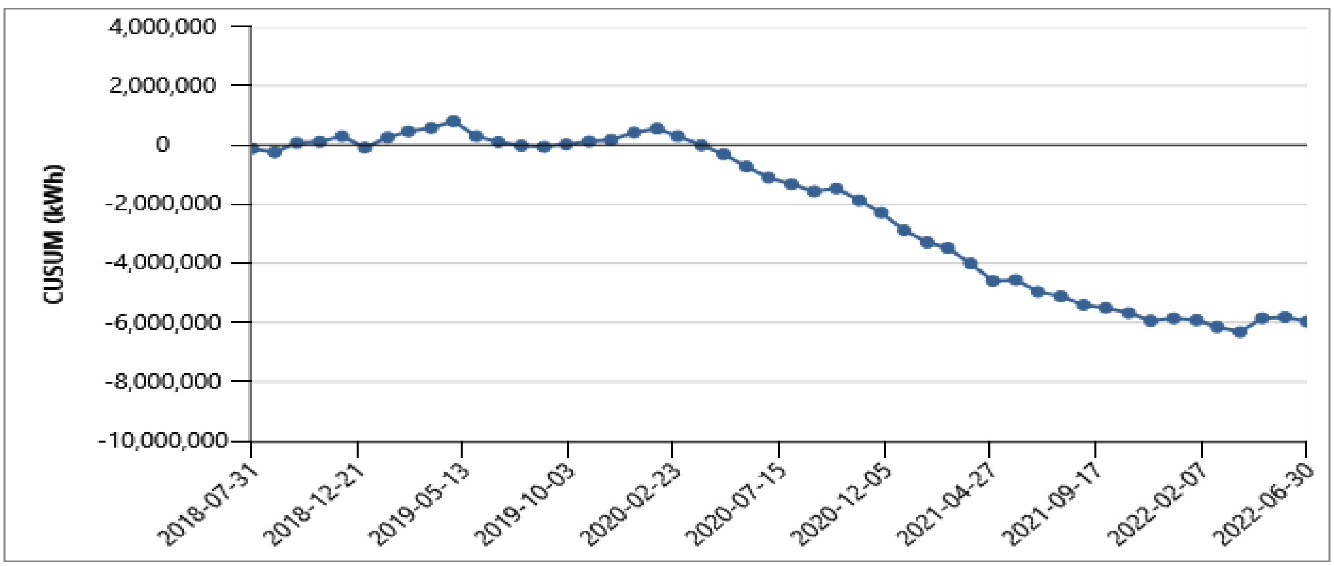

Figure 4.37: CUSUM of cement mills

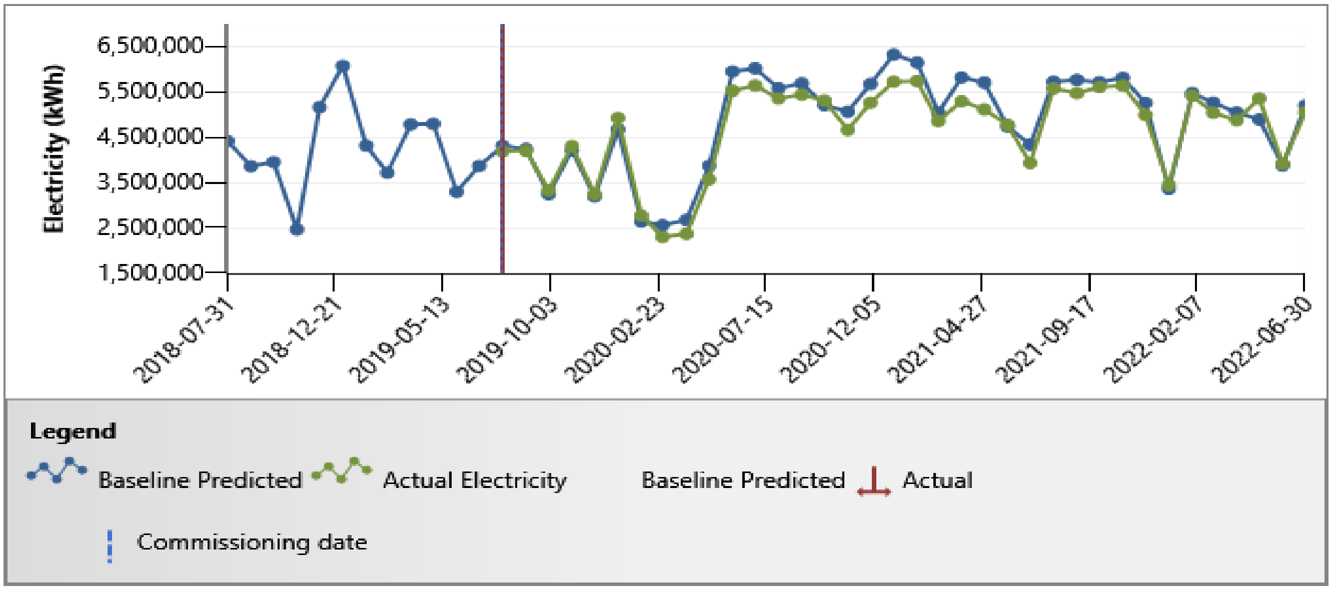

Figure 4.38: Measuring and verification of cement mills

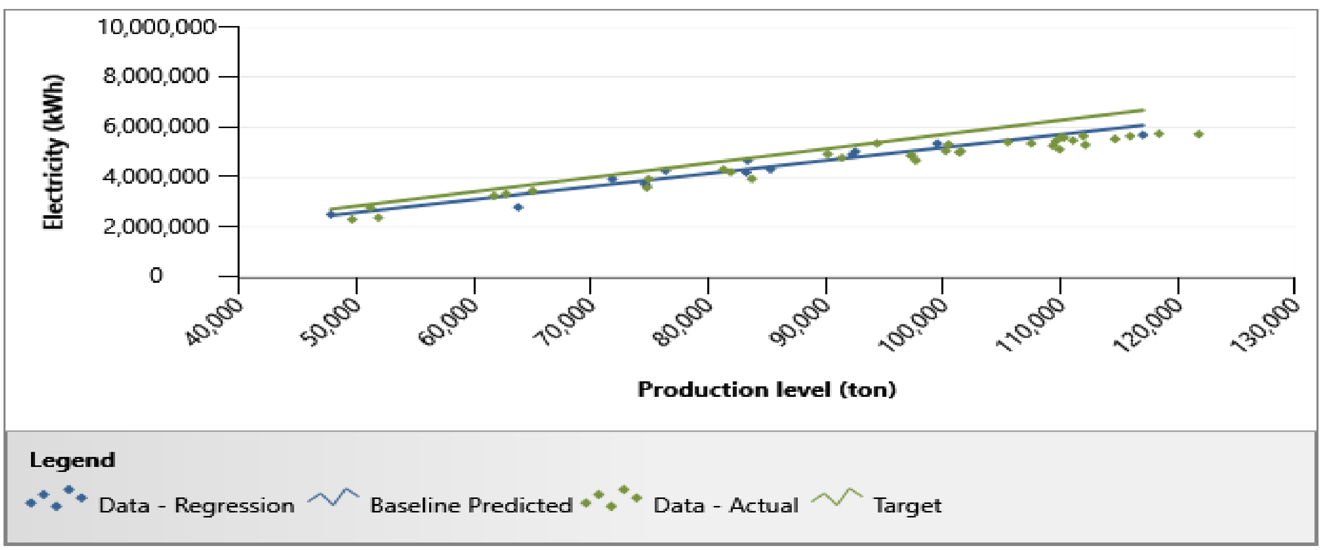

Figure 4.39: Target energy consumption saving of cement mills

The production performance of cement mills 1 and 2 is 75 tons per hour (t/h), which is approximately 75% of their design capacity, which is 100t/h. This indicates that the mills are operating at 75.3% efficiency. However, the specific energy consumption trend of cement mills as plotted in figure 4.33 shows not good energy performance trend for the 2018/2019 and relatively consumption decreased from 2020. This trend is also similar to the CUSUM, with net energy saving as of Mid-2022 showing 5,943, 707 Kwh shown in figure 4.37

4.2.3.5. Stoppage Analysis

The downtime data collected from the plant, indicates that the main downtime occurrences are related to the Vertical Roller Mill (VRM), two cement mills, and the Kiln. The primary causes of these downtimes are electrical system problems, mechanical maintenance issues, and power cutoffs and fluctuations. The kiln stoppages have a significant impact on the energy performance of the entire factory. The summary specifically for the Kiln is as follows:

By addressing the causes of Kiln downtime and improving its operational efficiency, the overall energy performance of the factory can be enhanced, leading to increased productivity and reduced energy wastage.

Table 4.24; Stoppage analysis summary from 2018/2019 – 2021/2022 downtime

Departments	stoppage hour in a year	%	Type	Remarks
External stoppage	1834.96	22.58	Unplanned	almost all due to power cut off and fluctuations from EEPCO
Production shut down	1183.28	14.56	Unplanned	
Mechanical stoppages	888.73	10.93	Unplanned	
Electrical stoppages	265.83	3.27	Unplanned	
Planning and Monitoring	3953.25	48.65	Planned	
Total	8126			

External factor stoppages are due to power cut off and Fluctuations from EEU

Planned; Kiln and gearbox maintenance

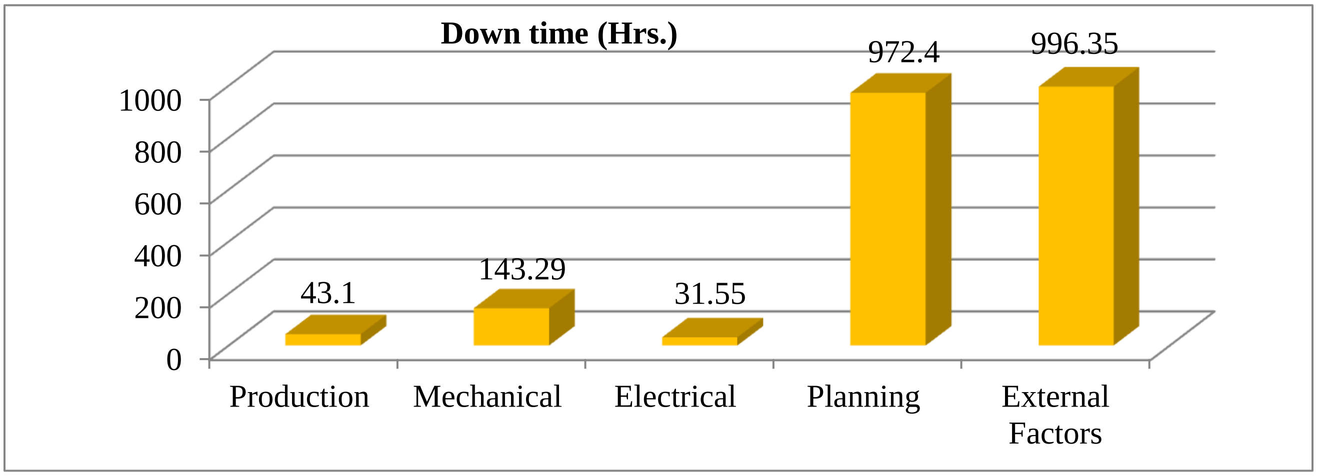

Figure 4.40: Kiln down time Vs Stoppage case in 2018/2019 year

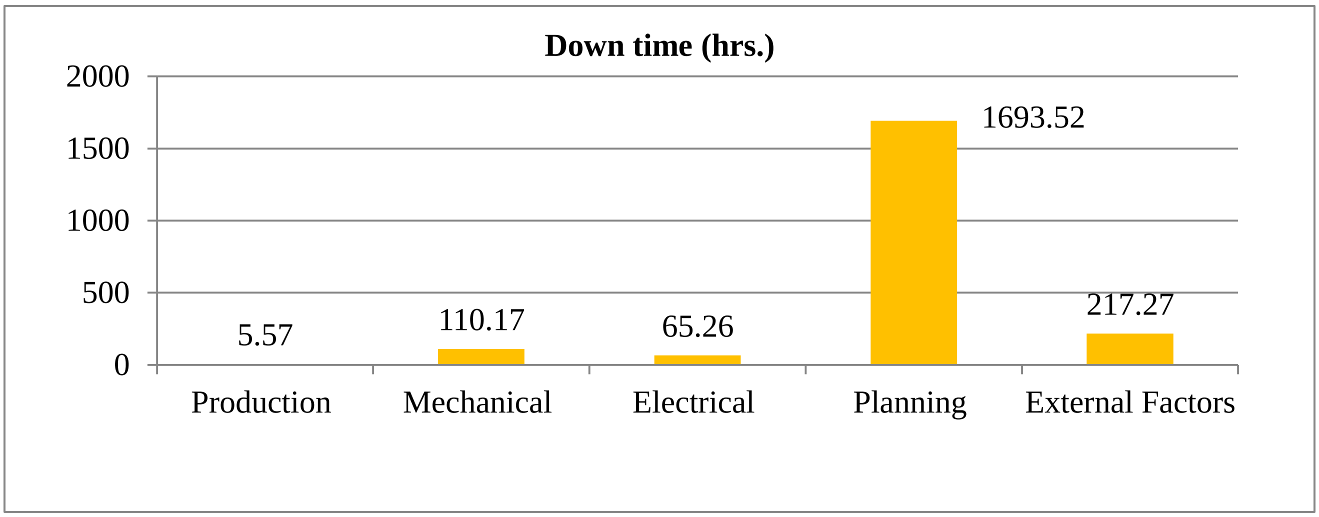

Figure 4.41: Kiln down time Vs Stoppage case in 2019/2020 year

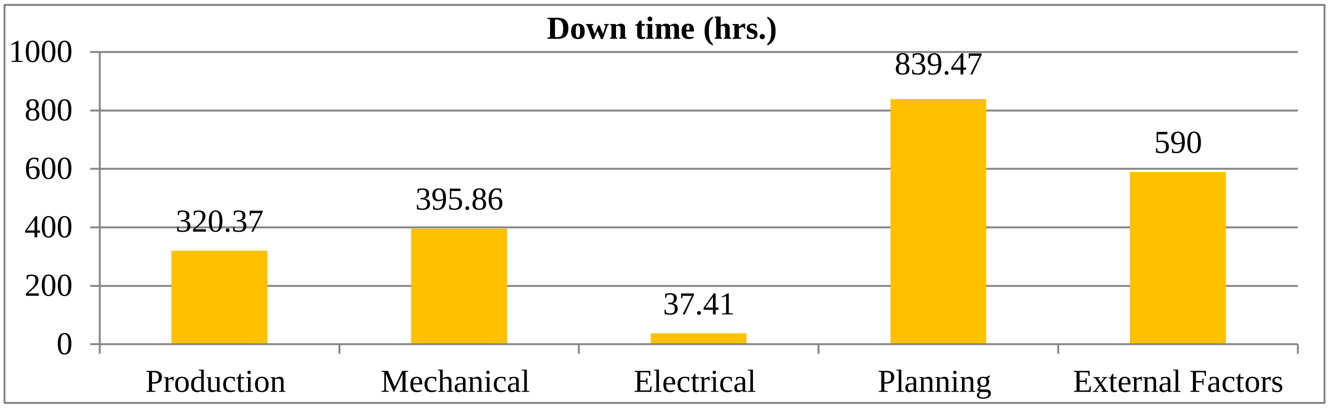

Figure 4.42: Kiln down time Vs Stoppage case in 2020/2021 year

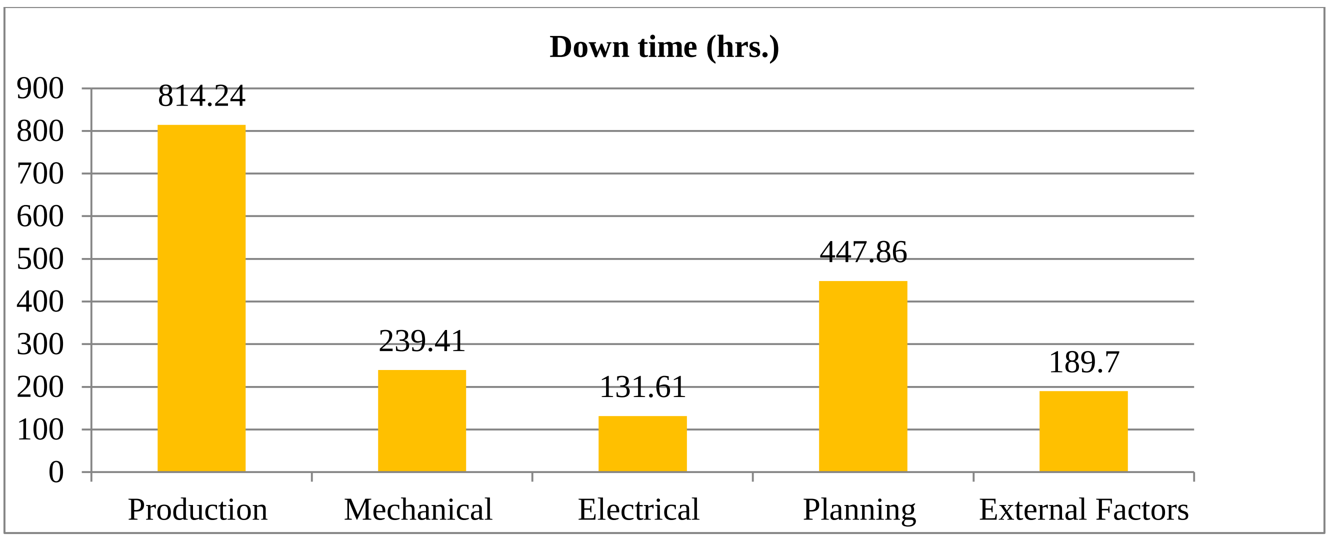

Figure 4.43: Kiln down time Vs Stoppage case in 2021/2022 year

Based on the revised details, the major downtime factor for the Kiln within the four-year auditing period was planning and monitoring, followed by external stoppages due to power cut-offs from the grid, and production stoppages.

The major downtime factors for the Kiln

The primary cause of major downtime for the Kiln was related to planning and monitoring. This suggests that issues related to scheduling, coordination, or inadequacies in monitoring the Kiln's performance may have led to extended periods of downtime. Improving planning processes, optimizing maintenance schedules, and implementing effective monitoring systems can help minimize this type of downtime.

The second major downtime factor for the Kiln was external stoppages caused by power cut-offs from the grid. These interruptions in the electrical supply, originating from factors beyond the facility's control, can have a significant impact on the Kiln's operation. Implementing West heat recovery Generator system can help to mitigate the effects of these power cut-offs.

The third major downtime factor was production stoppages. These stoppages occurred due to multiple reasons, including equipment failures, maintenance activities, process issues, or unforeseen circumstances. Enhancing preventive maintenance practices, improving equipment reliability, and optimizing operating procedures can help reduce production stoppages and minimize their impact on the Kiln's uptime.

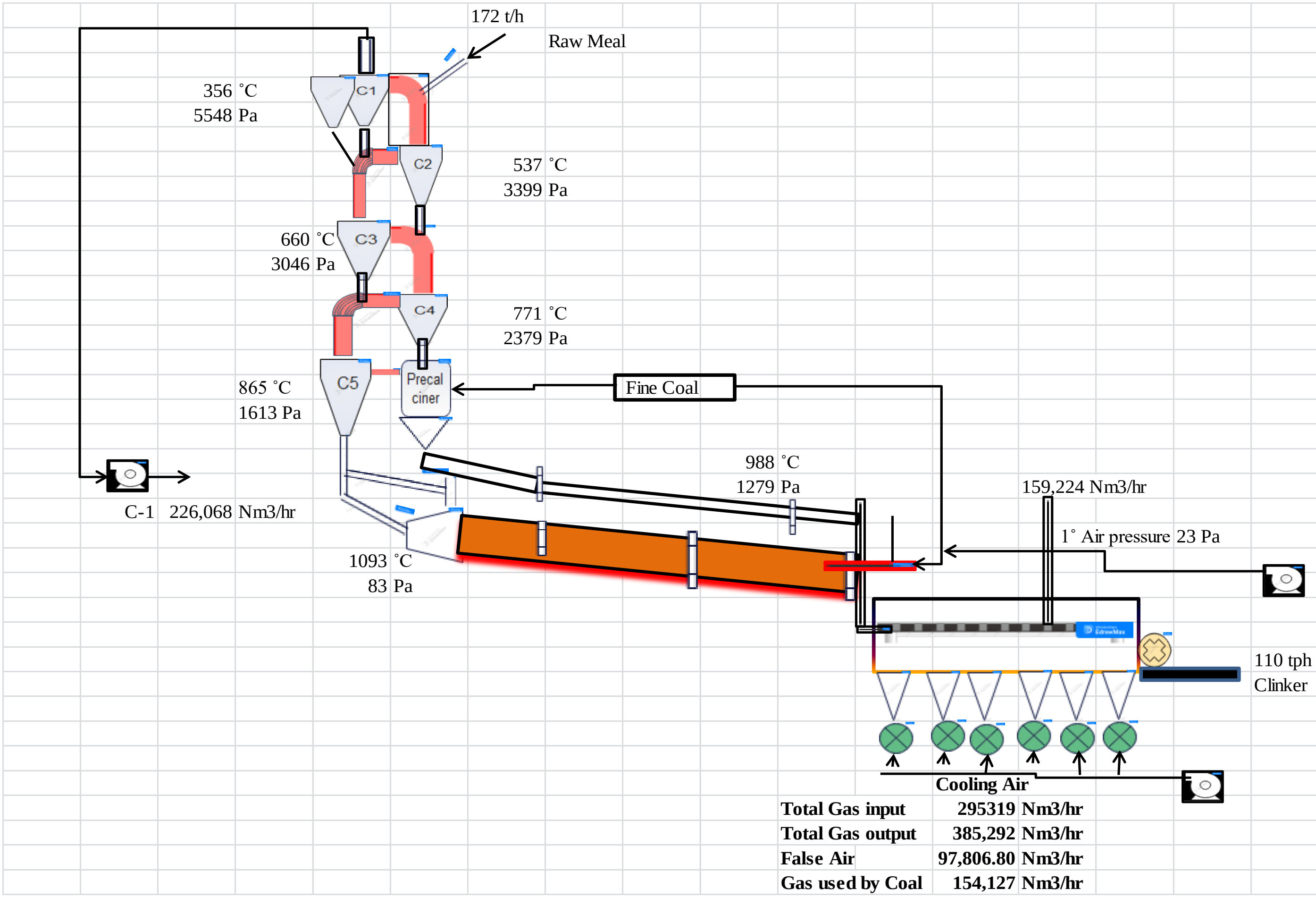

Figure 4.44: Pyroprocessing unit of 3000 tpd production line with input and output of tempreture and pressure steams

Available Energy from the Pyro processing for the design of Waste Heat Recovery System

There are more than 20 cements factories in Ethiopia. National cement factory is among the largest and former plants. In the country majority of cement factories their main source of power is electricity from of utility grid and imported fossil fuels like coal. Thus, they consume a lot of powers to perform their daily activity..

Due to the increase of human population and their demand of electricity increases parallel. So, peoples are searching an alternative option to meet their energy demand. Thus, they do either by introducing renewable source of energy, by hybridization different energy mixes or by optimization and increasing the efficiency of energy materials and equipment's. Besides these methods peoples are also started recovering the waste heat to generate power for different purposes. A model example of countries which are successfully produced power from waste of cement plants as

indicated in (*Sathiyamoorthy and Biglari, 2016*) are India, China and South-east Asian countries.
The first heat recovery system was established in Japan in 1980 by Kawasaki Heavy Industry KHI at Sumitomo Osaka Cement. Then after, a key project with 15 MW capacities has been released in Kumagaya plant (Taiheiyo Cement). After almost two decades later as stated in *(EC, 2015*) China was plant installed its first system in 1998 in partnership with a Japanese manufacturer. So, after many obstacles and modification we have reached in technology of waste heat recovery system to generate power from the flue gases. As described (Abnay 2017) some new generation of heat recovery installations in cement kilns producing up to 45 kWh per ton of clinker currently worldwide.
National cement share company utilize a large quantity of fuel and electricity that ultimately produce heat for a process and generates large amounts of exhaust heat during these manufacturing processes, as much as of the energy consumed is ultimately lost via waste heat, that simply passes out through the gas tubes (chimneys) into the atmosphere or into the surrounding without any recovery.

Waste Heat

Waste heat is the heat that is released into the environment by combustion or chemical reactions, that can be reused for useful and economic purposes (Karellas et al., 2013). Waste heat is emitted and released in a variety of ways, including radiation, cooling fluid, exhaust gas, and air, wherever products are produced, and machines are run (Bruckner et al., 2015). The authors further depicted that approximately 30% of the input energy is lost due to waste heat in the industrial sector
Generally, waste heat in high temperatures accounts for the higher quality waste recovery as well as more cost-effectiveness. Similarly, waste heat in low temperatures accounts for low-quality waste recovery with minimum cost-saving (Tafone et al., 2017).
The amount of waste heat (Q) can be calculated by using equation (1) (*Pehnt, bödeker et al. 2011*)

$Q = C.\ m.\ \Delta T$ .... [1]

Where m = the mass of the heat carrying medium

C = the heat capacity of the medium and

ΔT= the temperature difference between the waste heat and ambient temperature

4.2.4. Waste Heat Recovery System for Electricity Generation

A waste heat recovery system is a kind of technology used for the effective adoption of waste heat generated from different sources (Jouhara et al., 2018). Heat recovery in cement industries is an important aspect of energy efficiency and sustainability. Cement production is an energy-intensive process, and significant amounts of waste heat are generated during various stages of the cement manufacturing process. Heat recovery from the kiln system in cement industries is a crucial aspect of energy efficiency improvement. The kiln system, which includes the preheater, rotary kiln, and clinker cooler, generates a substantial amount of waste heat that can be captured and utilized for various purposes (Marenco-Porto et al., 2023). The calculated overall system efficiency obtained is 41% η (Heat of formation /Q total input) based on the ratio of heat of formation to total input heat indicates a relatively low level of energy utilization(Verma, Y. K., Mazumdar, B., & Ghosh, P. (2021). It is worth noting that some kiln systems operating at full capacity using the current dry process methodology can achieve higher efficiency levels, typically around 55%.

In light of the lower-than-desired system efficiency, it is crucial to explore opportunities for heat recovery in order to improve overall kiln system efficiency. By recovering and utilizing some of the heat losses within the system, it is possible to enhance energy utilization and increase the overall efficiency of the kiln system. Implementing heat recovery mechanisms, such as waste heat recovery systems or utilizing excess heat for other processes, can help reduce energy waste and improve the overall efficiency of the kiln system. These measures can contribute to cost savings, environmental sustainability, and overall operational efficiency.

The potential of electrical energy production from the lost thermal energy depends on the amount of volumetric flows and the temperatures of the pre-heater and grate cooler exhaust gases, the number of pre-heater steps, the moisture content of the raw materials, and the energy conversion efficiency of the WHRPG unit. Potential electrical energy production, typically ranging from 25 to 45 KW per ton of cement, using a WHRPG unit in cement factories with different production capacities(Zeb, Ali et al. 2017, Ghalandari and Rafsanjani 2019)

Table 4.25: Installed Waste Heat Recovery Projects in Pakistan(Zeb, Ali et al. 2017)

Plant	Kiln Type/ Capacity/No of lines	Year Started	Technology Provider	Total Installed Cost	WHR Capacity	CO_2 Savings t/y	Power Generation MWh/Y	Details
D.G khan Cement Dera Ghazi khan Plant	4/5 stage preheater/6,700 tpd/ 2 lines	2012	Anhui Conch/ Kwasaki Engineering	US$ 15 Million	10.4 MW	40,332	70,088	CDM;2 HRSG Installed on each kalin, one at pre-heater one on cooler.
D.G khan Cement Khairpur	Rotax 2/6,700 tpd/ 1 lines	2012	FLSmidth/ wasabi Energy	US$ 11.8 Million	8.5 MW	28,542	61,301	CDM; Kalina Cycle system
Cherat Cement	Rotary/3,200 tpd/ 1 lines	2011	Sinoma EC	US$ 9.3 Million	7 MW	25,761	41,730	CDM;2 HRSGs (3.7 TPH each) on free heater end & one HRSG(19.7TPH) On AQC
Attock cement Hub Chowki Plant	4×64 Rotary/ 5,200 tpd/ 2 lines	2011	Sinoma EC	US$ 18.6 Million	12 MW	37,908	58,320	CDM; IRR;9.1% (pre CER); Avg Gross 8.7 MW, Avg net 8.1 MW, Annual Savings US$3.6 m
Fecto Cement Sangjani Plant	Dry/2,600 tpd/ 1 lines	2010	CNBM	US$ 7.2 Million	6 MW	19,584	38,400	CDM;Project IRR:11.76%; EPC contract
Pezu Plant Unit(2)	Rotary/1,600 tpd/ 2 lines	2010	Anhui Conch/ Kwasaki Engineering	US$ 19.56 Million	16.5 MW	49,785	101,851	CDM; IRR;11.54% (pre CER);annual Saving US$3.9 m
Lucky Cement	Dry/3.6 Mta	2009	Anhui Conch/ Kwasaki Engineering	US$ 12.6 Million	15 MW	48,060	108,000	CDM; Pre heater & coolers
Karachi Plant	Rotary/6,600 tpd/ 2 lines	2009	Sinoma EC	US$ 9.1 Million	10 MW	33,820	58,291	CDM;Project IRR;7.95% (pre CER);EPC contract
Lucky Cement	Dry/9,000 tpd/ 3 lines	2008	Sinoma EC	US$12.54 Million	15 MW	42,992	87,437	CDM;Project IRR;7.39% (pre CER);EPC contract

The common areas where waste heat recovery is implemented in cement industries are; Preheater and Cooler Exhaust Gases: The preheater and cooler systems in cement plants produce hot exhaust gases. These gases can be utilized to preheat the raw materials entering the kiln or to generate steam for electricity generation or other industrial processes. Heat exchangers or waste heat boilers are commonly used to recover heat from these exhaust gases.

Based on these two highest waste heat sources, our waste heat recovery system is designed The main tapping spots are the exhaust pipe before it enters into the induced draught fan and after the first cyclone from the top for the kiln exhaust and the pipe just after the hot air leaves the cooler stack and before it goes the heat exchanger and ESP for the cooler side.

The exhaust gas from the preheater is 386˚C and the temperature of the air exhausted from the cooler stack is 290˚C. These two streams would be going through a waste heat recovery steam generator (WHRSG), and the available heat energy is transferred to water via the WHRSG as shown in Fig4.45. The available waste energy could generate steam. This steam is used to run a steam turbine to drive electrical generator. The generated electricity could cover the electrical consumption of the kiln system.

The available energy that can be harnessed/ conserved from the preheater exhaust gas and cooler vent hot air can be calculated as shown below.

The heat available from preheater and cooler exhaust can be calculated as:

Q exh _ pht= Preheater exit gas energy; Q exh _ cool= Cooler exhaust gas energy

Q available = Q exh _ pht + Q exh _ cool

The available energy transferred to WHRSG in the form of work is defined as

Net heat recovered = net heat available * efficiency of WHR system

$Q_{WHRSG} = \eta Q_{Available}$ (Zhang et al., 2019)

Table 4.26: Waste heat recovery calculation from preheater and cooler exhaust

NCSC-Waste Heat Recovery calculation										
Clinker production	3000	tpd								
	3000000	kg								
	125	tph								
Preheater exit gas energy										
Specific PHT gas flow	1.8085	Nm3/kg Clinker								
PHT exit gas flow	226,068	Nm3/h			**Tin**	**386**	° C	**Tout**	**160**	° C
					Specific heat	**Heat**		**Specific heat**	**Heat**	
Gas composition	%	Nm3/hr	kg/h	Molar mass (kg/kmol)	**(kcal/kg °C)**	**(kcal/hr)**		**(kcal/kg °C)**	**(kcal/hr)**	
N2	62	140162.16	175063	28	0.252	17028683		0.244	6834441.5	
CO2	26.2	59229.816	116268	44	0.235	10546682		0.2007	3733602.2	
O2	4.4	9946.992	14201.3	32	0.23	1260793.2		0.218	495342.06	
SO2	0	0	0	32	0.169	0		0.159	0	
H2O	7.4	16729.032	13434.6	18	0.464	2406187.7		0.443	952243.29	
Gas total	100	226068	318967			31242346			12015629	
PHT dust (CaO)	85.00%	g/Nm3	1921.58		0.203	150571.01		0.193	59338.329	
		mass in	320888			31392917			12074967	
Molar volume of ideal gas	22.414	m3/kmol			Net heat available	19317950	kcal/h			
						22466.776	kw			
						154.5436	kcal/kg clinker			
						179.7342	kwh/t Clinker			

Cooler Exhaust gas energy										
Specific Cooler gas flow	1.2738	Nm3/kg Clinker								
Cooler Exhaust gas flow	159,224	Nm3/h			**Tin**	**290**	° C	**Tout**	**110**	° C
					Specific heat	**Heat**		**Specific heat**	**Heat**	
Gas composition	%	Nm3/hr	kg/h	Molar mass (kg/kmol)	**(kcal/kg °C)**	**(kcal/hr)**		**(kcal/kg °C)**	**(kcal/hr)**	
N2	79	125786.96	157108	28	0.25	11390324		0.244	4216776.4	
CO2	0	0	0	44	0.224	0		0.201	0	
O2	21	33437.04	47738.1	32	0.226	3128753		0.22	1155261.1	
SO2	0	0	0	32	0.162	0		0.169	0	
H2O	0	0	0	18	0.456	0		0.443	0	
Gas total	100	159224	204846			14519076			5372037.5	
PHT dust (CaO)	30.00%	g/Nm3	477.672		0.197	27289.4		0.193	10140.977	
		mass in	205324			14546366			5382178.5	
Molar volume of ideal gas	22.414	m3/kmol			Net heat available	9164187	kcal/h			
						10657.95	kw			
						73.3135	kcal/kg clinker			
						85.2636	kwh/t clinker			

Table 4.27: Net heat recovered from preheater and cooler exhaust

Net heat recovered		
Preheater exit gas energy	179.734205	kwh/t clinker
cooler exhaust gas energy	85.2635979	kwh/t clinker
	264.997802	kwh/t clinker
Efficiency of WHR	20	%
Net heat recovered	**52.9995605**	**kwh/t clinker**

Heat available out of the preheater exhaust gases is 22,467kJ/s = (179.734) x 3000 /24); Qexh_pht=22,467kJ/s

Heat available out of the cooler exhaust gases is 14573kJ/s = (85.26) x 3000 / 24) ;

Qexh_cool=10658 kJ/s

Total net heat available is 53kWh/t clinker. Assuming that all of it is used and the WHR system will have 20% efficiency, this result in power production of 6.63MW (53 x 3000 / 24 /1000 = 6.63 MW)

Proposed waste heat integration system

Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle. This thermodynamic cycle is the basis for conventional thermal power generating stations and consists of a heat source (boiler) that converts a liquid working fluid to high-pressure vapor (steam, in a power station) that is then expanded through a turbo generator producing power. Low-pressure vapor exhausted from the turbo generator is condensed back to a liquid state, with condensate from the condenser returned to the boiler feed water pump to continue the cycle. Waste heat recovery Rankine cycles can be based on steam or on an organic compound used as the working fluid. In each case, the working fluid is vaporized in heat recovery boilers or steam generators (HRSGs) by the hot exhaust gases from the preheater and hot air from the cooler, and then expanded through a turbine that drives a generator.

Steam rankine Cycle (SrC) – The most commonly used Rankine cycle system for waste heat recovery power generation uses water as the working fluid and involves generating steam in a waste heat boiler, which then drives a steam turbine. Steam turbines are one of the oldest and most versatile power generation technologies in use. As shown in Figure 4.50, in the steam waste heat recovery steam cycle, the working fluid—water—is first pumped to elevated pressure before entering a waste heat recovery boiler. The water is vaporized into high-pressure steam by the hot exhaust from the process and then expanded to lower temperature and pressure in a turbine, generating mechanical power that drives an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where the expanded vapor is condensed to low-pressure liquid and returned to the feed- water pump and boiler.

Steam cycles are by far the most common waste heat recovery systems in operation in cement plants, and generally reflect the following:

- Most familiar to the cement industry and are generally economically preferable where source heat temperature exceeds 300° C (570° F)
- Based on proven technologies and generally simple to operate
- Widely available from a variety of suppliers
- Generally have lower installation costs than other Rankine cycle systems on a specific cost basis (US$/kW)
- Need higher-temperature waste heat to operate optimally (minimum >260° C (500° F))—generation efficiencies fall significantly at lower temperatures, and lower pressure a temperature steam conditions can result in partially condensed steam exiting the turbine, causing blade erosion
- Often recover heat from the middle of the air cooler exhaust flow to increase waste gas temperatures to an acceptable level for the system, but at the expense of not recovering a portion of cooler waste heat Often require a full-time operator, depending on local regulations

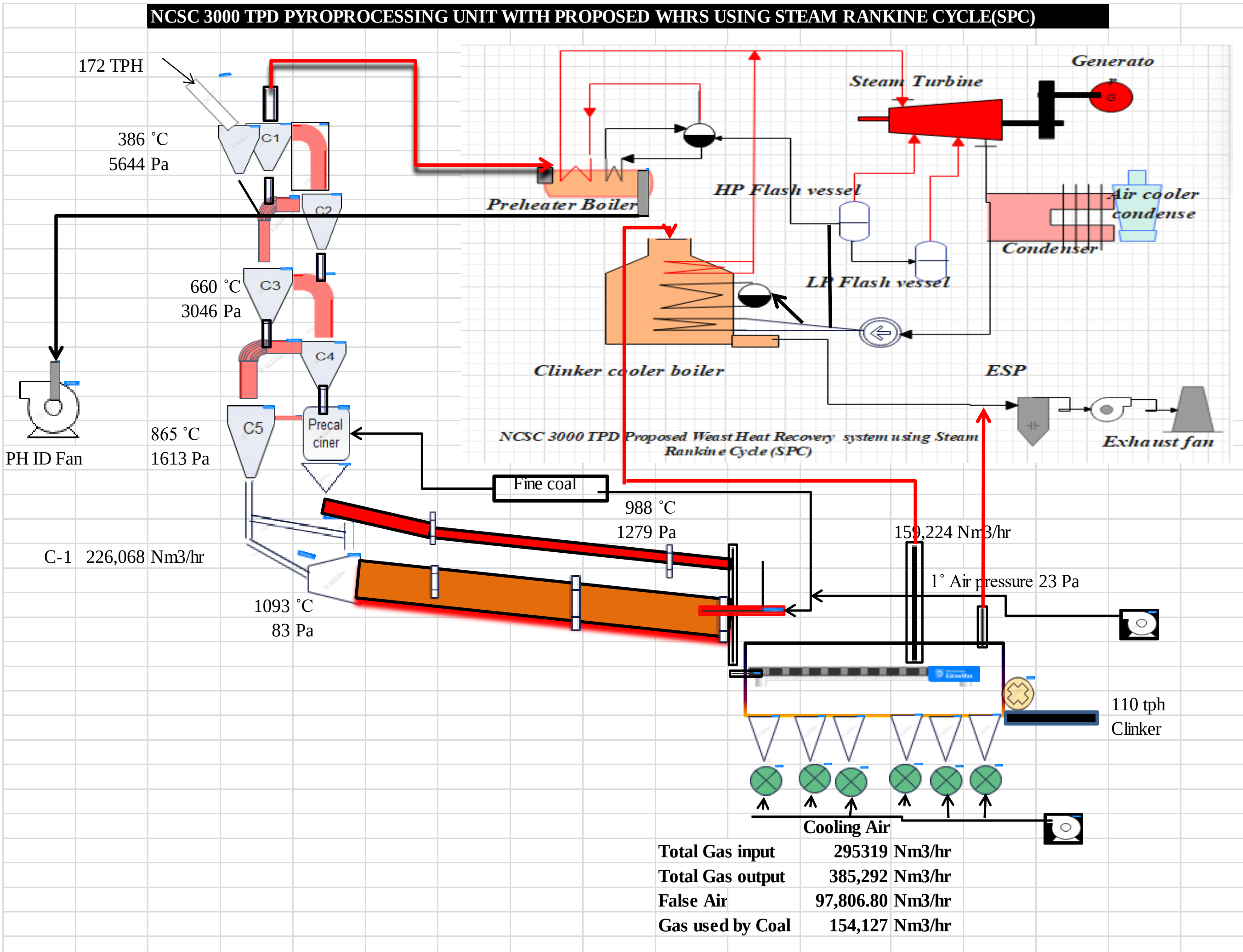

Figure 4.45: Proposed waste heat recovery steam generator system for power generation

Preheater Boiler: Installed between preheater exhaust gas duct and preheater ID fan

Clinker Cooler Boiler: Installed between clinker cooler and ESP inlet

Economic feasibility

The initial investment cost of the WHRPG unit includes design, engineering services, construction structures, types of technology and equipment. These costs vary according to the geographic location of the factory, the distance from the electricity distribution main lines and the manufacturing technology. It should be noted that the initial investment cost is strongly dependent on the size and capacity of the WHRPG unit in such a way that by reducing the unit size, the investment cost per kilowatt of production is increased. About 34% to 45% of the initial investment cost includes engineering services and construction structures. The cost of installing the WHRPG unit in the European countries is highest and in China is the lowest. Fig. 8 shows the cost of installing Chinese WHRPG units in different parts of the world. The cost of installing Chinese systems is typically about 20% to 30% cheaper than similar systems in European countries (Brückner, Liu et al. 2015, Yang, Hung et al. 2017)

To calculate the cost and payback period for the installation of a Waste Heat Recovery System of NCSC (WHRS) utilizing Preheater exhaust and cooler exhaust with a power generation capacity of 6.63 MW, let's consider the measured exhaust parameters:

- PH Exhaust Temperature: 386°C and Flow Rate, 226,068 Nm3/hr.
- Cooler Exhaust Temperature; 290°C and Flow Rate, 159,224 Nm3/hr.
- A WHRS system is chosen to harness the waste heat from both preheater exhaust and cooler exhaust.
- The waste heat recovery system can generate electricity from the preheater is 4.3 MW of electricity.
- The waste heat recovery system can generate electricity from the cooler exhaust is 2.33 MW of electricity generation.

Capital Investment: The total capital investment for the WHRS installation, including equipment, modifications, and installation costs, varies depending on the specific technology chosen. Let’s assume a total capital investment of 10 million.

Cost of operation and maintenance of the system which is typically about 2.5% of the initial investment cost per annum for the steam Rankine cycle (SRC) unit. The Kiln operating hours per year for NCSC is 7200 hours and Electricity costs /prices per megawatts hour in Ethiopia is 37.35 USD.

In Table 4.28: the investment cost of purchasing and installing a 6 MW unit of WHRPG with SRC technology for the NCSC plant and the time of return on capital are illustrated. As can be seen, the rate and time of return of capital are 15% (in the year) and 9.2 years, respectively

Table 4.28: Economic feasibility of 3000tpd NCSC WHRPG

WHRPG Payback calculations	**Amount**
Clinker production	125,000 kg/hr.
Net generated electrical energy	6.63 MWh
Annual working hours of system	7200 hrs.
Annual net generated electrical energy	47736 MWh.
The purchase price of electrical energy	37.35 USD/MWh
Annual gross income from the sales of electrical energy	1,782,939.6 USD
Total initial investment	10000000 USD
Annual maintenance cost(2.5% of initial investment)	250000 USD
Tax (25%)	445734.9 USD
Annual net income from the sale of electrical energy	1087204.7
The rate of return of capital (in the year)	11%
Time of return of capital	9.2 years

5. Conclusion and Recommendation

5.1. Conclusion

In this study, a thermal energy audit analysis was conducted on the pyro-processing unit of a National Cement Plant using dry process rotary kiln technology. The objective was to assess the distribution of input heat energy within the system components and identify areas of significant thermal energy loss. The analysis revealed good agreement between the total input and output energy, indicating that the energy balance within the pyro-processing unit was well-maintained. However, the findings also indicated that the overall system efficiency was relatively low, with a calculated value of 41% based on the ratio of heat of formation to total input heat. The analysis showed that the preheater exhaust accounted for 23% of the total input energy, indicating a substantial loss of heat in this area. The combined radiation and convective surfaces, which include the kiln, precalciner, and preheater, accounted for 14.02% and cooler exhaust accounted for 13.04% of the total input energy. Recognizing the potential for heat recovery from these sources, a Waste Heat Recovery Steam Generator (WHRSG) system was selected and designed. By implementing the WHRSG system, a significant amount of thermal energy could be recovered and converted into electricity. Specifically, 6.63 MW of electricity could be produced using a steam Rankine cycle. The economic feasibility of this heat recovery mechanism was also assessed, with a projected rate of return on capital of approximately 11% per year.

An electrical energy audit was conducted on the main equipment in the process unit of the Cement Plant. The audit utilized RETScreen software to evaluate potential energy and monetary savings, identify energy-saving opportunities, estimate potential savings, and assess the financial impact of implementing energy efficiency measures. The findings indicate that the Coal Mill (361,157 kWh) and Cement Mills (5,943,707 kWh) achieved net energy savings compared to the baseline period, as evidenced by the predicted energy consumption model equation. These energy savings have already been realized. However, the Raw Mill (1,943,363 kWh) and the Kiln (7,321,449 kWh) exhibited a trend of energy wastage in comparison to the baseline period. The total energy and monetary savings were determined accordingly, with an estimated potential saving of approximately 14.4 million birr. This calculation is based on the current rated power cost of 0.928 birr/kWh from the EEU (grid) to the National cement plant.

During the four-year auditing period, the major downtime factor for the Kiln in the National Cement Plant was planning and monitoring issues, followed by external stoppages due to power cut-offs from the grid. The total duration of stoppages caused by power interruptions from the grid was 1834.96 hours. The plant incurred a production loss of 229,370 tons over the four-year period. Additionally, the monetary loss due to these production losses amounts to 1,720,275,000 Ethiopian Birr (ETB) within the four-year duration, equivalent to 430,068,750 ETB per year. These figures highlight the significant impact of power interruptions on the plant's productivity and financial performance.

5.2. Recommendation

To improve the thermal and electrical efficiency of the plant, I recommend that ; installing proper refractory materials on the high-temperature preheater cyclone surface to minimize heat losses and improve the thermal efficiency of the plant, process optimization in the combustion process in the kiln by adjusting parameters such as fuel-to-air ratio, and temperature profile, regularly monitor and evaluate the energy performance of the plant, conduct energy audits, and identify any changes in heat loss patterns, Implement waste heat recovery systems, such as Waste Heat Recovery Steam Generators (WHRSG), to capture and utilize excess heat from the preheater exhaust and cooler exhaust. This recovered heat can be used for electricity generation or as a heat source for other processes within the plant, Upgrade motors to high-efficiency models and implement variable frequency drives (VFDs) to match motor speed with process requirements, reducing energy waste and Find solutions to mitigate power cut-offs from the grid to minimize production losses and improve operational efficiency. This could involve backup power systems, grid stability measures, or alternative power sources.

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APPENDEX

Table A. kiln shell temperatures measured along with kiln length (K)

Distance (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Ave tem(K)	658	658	588	588	583	583	564	564	519	519	507	507	461	461	645	645	619	619	650	650	522	522	530	530	590	590	639	639	518	518	630	630

Distance (m)	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
Ave tem(K)	612	612	617	617	614	614	551	551	554	554	509	509	522	522	515	515	506	506	512	512	503	503	504	504	516	516	579	579	575	575	577	577

Table B. Cooler surface temperatures measured along with length (K)

Distance (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ave tem(K)	345	352	357	353	357	366	362	411	371	378	384	386	387	391	396	402	414	426	430	441	463	453

Table A. Monthly production and energy consumptions data for raw mill from 2018/2019 – 2021/2022

	Production (ton) ; 2018/2019 – 2021/2022				Power consumption (kwh);2018/2019- 2021/2022			
Month	**2018/2019**	**2019/2020**	**2020/2021**	**2021/2022**	**2018/2019**	**2019/2020**	**2020/2021**	**2021/2022**
July	148,503.00	140,553	124,943	141,569.74	3,751,826	3,604,483	3,247,298	3,531,923
August	132,321.00	138,265	129,952	140,247.61	3,244,758	3,631,704	3,033,141	3,627,622
September	78,668	117,272	52,004	127370.98	1,948,417	3,259,453	1,251,086	3,232,743
October	20,568	38,626	136,229	142450.28	551,523	1,221,520	3,716,464	3,570,036
November	140,848	145,277	103,250	34813.3	3,516,196	3,384,743	2,731,970	1,086,161
December	136,452	136,239	127,355	116146.78	3,163,249	3,473,903	3,403,099	2,881,478
January	137,005	142,700	137,812	141554.35	3,544,167	3,211,722	3,440,175	3,454,939
February	133,429	100,946	109,799	58136.039	3,200,584	2,547,037	3,053,354	1,670,431
March	97,788	139,104	83,096	69533.753	2,533,685	3,302,450	2,066,918	1,746,179
April	133,699.00	20,224	129,553	114,121.59	3,481,422	626,173	3,219,241	3,128,496
May	93,983.00	27,499	109,716	92,146.06	2,062,578	562,071	2,900,513	2,402,557
June	73,544.00	130,652	21,978	118,370.56	1,920,137	3,265,807	542,165	3,181,716
SUM	1,326,808	1,277,358	1,265,688	1,296,461	32,918,541	32,091,066	32,605,424	33,514,281

Table B. Monthly production and energy consumptions data for Coal mill from 2018/2019 – 2021/2022

	Production (ton)				Power consumption (kwh)			
Month	2018/2019	2019/2020	2020/2021	2021/2022	2018/2019	2019/2020	2020/2021	2021/2022
July	13,714.00	12,756	12,689	14,336.00	631,928	330,598	267,232	343,268
August	12,259.00	12,684	12,176	13,614.80	510,561	334,809	250,977	388,988
September	7,106	10,851	5,046	11989	339,635	272,498	88,498	389,264
October	2,547	3,745	12,879	13472	129,629	128,125	226,487	382,719
November	12,464	12,594	9,815	3414	280,619	348,625	214,042	136,393
December	12,422	12,205	12,266	13047	276,801	333,794	266,665	311,598
January	12,843	12,221	13,279	14036	338,688	610,652	335,522	348,937
February	12,441	9,134	10,881	6301	304,264	221,872	304,928	215,808
March	8,592	12,545	9,143	10456	266,390	254,961	206,985	249,010
April	11,889.00	2,060	13,036	16,640.00	345,589	36,970	388,830	395,563
May	8,003.00	2,278	10,818	13,095.00	182,027	40,776	276,815	301,384
June	6,324.00	9,192	2,903	21,737.00	144,825	275,340	76,967	388,605
SUM	120,604	112,265	124,931	152,138	3,750,956	3,189,020	2,903,948	3,851,537

Table C: Monthly production and energy consumptions data for Kiln from 2018/2019 – 2021/2022

	Production (ton)				Power consumption (kwh)			
Month	2018/2019	2019/2020	2020/2021	2021/2022	2018/2019	2019/2020	2020/2021	2021/2022
July	96,441.32	92,004	83,399	89,722.00	3,621,864	3,654,565	3,531,209	3,668,600
August	86,444.31	90,110	81,476	91,180.00	3,098,241	3,546,716	3,366,416	3,644,978
September	48,174	75,248	33,259	82400	2,101,134	3,170,413	1,628,053	3,336,702
October	16,231	27,399	85,710	91994	872,809	1,558,844	3,392,046	3,717,025
November	87,290	89,088	66,230	22012	3,454,015	3,578,627	2,875,067	1,416,691
December	88,113	87,070	80,700	76625	3,220,677	3,508,877	3,437,037	3,243,368
January	89,632	90,373	88,021	86688	3,616,740	3,502,086	3,650,152	3,682,088
February	84,930	66,933	69,510	37488	3,334,623	2,864,442	2,979,920	2,070,879
March	61,778	92,275	55,843	47934	2,704,271	3,580,161	2,364,487	2,205,858
April	87,265.27	14,250	83,940	74,629.00	3,651,794	975,988	3,414,367	3,533,395
May	59,560.48	15,334	69,403	55,347.00	2,037,226	713,708	3,091,530	3,019,459
June	46,495.21	85,957	17,621	81,559.00	2,061,945	3,573,943	1,064,826	3,721,104
SUM	852,356	826,042	815,111	837,578	33,775,340	34,228,370	34,795,110	37,260,147

Kiln Down Time July,2018 - June ,2019

Months	Down Time (hrs.) in dep't				
	Production	Mechanical	Electrical	Planning	External Factors
7/31/2018	0.13	5.77	1.4	0	5.25
8/31/2018	1.67	0.38	10.7	52.92	13.98
9/30/2018	6.08	0	1.25	314	11.92
10/31/2018	0.4	0	5.6	605.48	0.67
11/30/2018	27	7.92	2.5	0	1.45
12/31/2018	7.82	70.53	0.97	0	13.48
1/31/2019	0	47.02	7.98	0	5.05
2/28/2019	0	7.2	0.1	0	5.17
3/31/2019	0	0	0.3	0	252.96
4/30/2019	0	4.47	0.75	0	45.53
5/31/2019	0	0	0	0	278.17
6/30/2019	0	0	0	0	362.72
Total (hrs.)	**43.1**	**143.29**	**31.55**	**972.4**	**996.35**
type of stoppage	Unplanned	Unplanned	Unplanned	Planned	Unplanned

Kiln Down Time July,2019 - June ,2020

Months	Down Time (hrs.) in dep't				
	Production	Mechanical	Electrical	Planning	External Factors
7/31/2019	0	3.01	5.81	0	3.28
8/31/2019	0	0	0	0	4.13
9/30/2019	0	28.75	41.95	0	41.17
10/31/2019	0	14	0.28	503.13	4.62
11/30/2019	0.2	0	1.32	0	11.53
12/31/2019	0	18.22	0	1.5	6.77
1/31/2020	0	18.75	0	0	5.45
2/28/2020	0	27.44	1.12	0	115.77
3/31/2020	0	0	6.93	0	10.3
4/30/2020	0	0	2	570.33	1.8
5/31/2020	0	0	0.25	610.83	3.05
6/30/2020	5.37	0	5.6	7.73	9.4
Total (hrs.)	**5.57**	**110.17**	**65.26**	**1693.52**	**217.27**
type of stoppages	Unplanned	Unplanned	Unplanned	Planned	Unplanned

Kiln Down Time July,2020 - June ,2021

Months	Down Time (hrs.) in dep’t					
	Production	Mechanical	Electrical	Planning	External Factors	***External factor*** stoppages are due to power cut off and Fluctuations from EAU ***Planned***; Kiln and gearboxmaintenance
7/31/2020	44.68	1.83	1.43	0	32.77	
8/31/2020	17	18.05	7.65	0	46.05	
9/30/2020	0	6.8	0.3	445.33	0	
10/31/2020	0	2.5	6.67	0	47.03	
11/30/2020	179.33	0	0	0	15.08	
12/31/2020	53.62	7.22	0.37	0	27.83	
1/31/2021	0	4.92	1.17	0	23.58	
2/28/2021	0.88	13.27	0	0	80.1	
3/31/2021	0	5.22	4.35	0	276.25	
4/30/2021	9.28	4.5	4.27	0	33.55	
5/31/2021	15.58	16.92	5.32	147.67	6.53	
6/30/2021	0	314.63	5.88	246.47	1.22	
Total (hrs.)	**320.37**	**395.86**	**37.41**	**839.47**	**590**	
Type of stoppages	Unplanned	Unplanned	Unplanned	Planned	Unplanned	

Kiln Down Time July,2021 - June ,2022

Months	Down Time (hrs.) in dep’t					
	Production	Mechanical	Electrical	Planning	External Factors	Quality
7/31/2020	0.00	1.33	19.38	0.00	0	0
8/31/2020	0.00	4.48	7.00	0.00	0.92	0
9/30/2020	0.00	11.82	11.18	41.25	7.27	0
10/31/2020	0.00	7.47	1.67	0.00	1.10	0
11/30/2020	131.75	24.00	0.92	382.08	0.00	0
12/31/2020	3.42	126.52	4.90	0.00	3.78	0
1/31/2021	1.08	9.75	4.55	6.08	18.08	5
2/28/2021	335.12	3.60	7.17	18.45	3.15	0
3/31/2021	319.34	7.47	8.11	0.00	0.97	0
4/30/2021	21.90	7.87	8.33	0.00	18.28	0
5/31/2021	0.33	27.40	55.15	0.00	127.53	16.92

6/30/2021	1.30	7.70	3.25	0.00	8.62	9.17
Total (hrs.)	**814.24**	**239.41**	**131.61**	**447.86**	**189.70**	**31.34**
Type of stoppages	Unplanned	Unplanned	Unplanned	Planned	Unplanned	Unplanned