Assessing the Potential of Demand-Side Energy Management in the Cement Industry:

Exploring Energy Efficiency, demand flexibility, and onsite power generation potentials within the context of the Ethiopian Cement Sector

Doctoral Thesis

By

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Abstract

Ensuring reliable energy access is crucial for sustainable development and economic growth. The challenges posed by the growing energy demand can be approached through supply-side energy management. However, this task has become increasingly challenging due to the high fluctuating electricity demand and the growing share of intermittent renewable energy sources in the electricity supply mix. In response to these challenges, demand-side management (DSM) has emerged as a key strategy in modern energy systems to address grid stability, enhance energy efficiency, and promote sustainability. This PhD study investigates an industrial demand-side energy management system, focusing on improving energy efficiency, implementing demand response strategies and promoting onsite power generation in the cement industry. The cement industry is notably recognized as one of the most energy-intensive and emission-heavy industries. Hence, it is important to assess the potential of demand-side energy management in this sector. The energy efficiency improvement opportunities are explored with the help of a benchmarking tool, while a mixed integer non-linear programming model is developed to evaluate the sector's energy demand flexibility, aiming to achieve energy savings, grid balancing, and climate mitigation goals. The potential and viability of waste heat recovery power generation are investigated by estimating the power output capacity, life cycle costs, levelized cost of energy, and net present values for three different waste heat recovery technology options.

The energy and environmental performances of the Ethiopian cement industry are first assessed and compared against best practices with the help of a Benchmarking and Energy Saving Tool for Cement (BEST-Cement). The results reveal that all the surveyed plants are less efficient, with an average energy saving potential of 36% indicating a significant potential for energy efficiency improvement. Then, potential energy efficiency measures (EEMs) have been identified and analyzed using a bottom-up energy conservation supply curve (ECSC) model. The findings show that the cost-effective electrical energy and fuel-saving potentials of these measures are estimated to be 99 Gigawatt hours per year which is about 11.5% of the plants' annual electrical energy consumption and, 2.7 Petajoules per year which is 12.5% of the plants' annual fuel consumption, respectively. The cost-effective fuel measures have an annual average CO_2 emission reduction potential of 254 kilo-tonnes per year which covers about 5% of the total CO_2 emission. The technical potential for saving electrical energy and fuel of the measures in each category amounted to 33% and 14%, respectively, of the annual energy consumption of the surveyed cement plants. Sensitivity analysis is conducted using the key parameters that show some discrepancy in the base case results.

To assess the energy demand flexibility potential of the cement industry, an energy consumption optimization model of the industrial demand response for conventional power grids has been developed, aiming to flatten the hourly demand curve of the grid by minimizing the industrial customer's hourly peak loads and maximizing the shifting of demand to off-peak periods.

The result demonstrates that the demand flexibility potential of the case study cement plants is about 495 MWh per day, constituting approximately 28% of the daily total electrical energy used by these cement plants, proving that the cement industry is a potential candidate for demand response strategies. By adapting the proposed model, the loads of the case study plants during the peak period of the day are reduced by an average of 75%. In addition, an overall reduction of 188 tonnes of CO_2 emissions per day has been achieved in case study plants. Furthermore, the cost of consumed electrical energy for a day decreased on average by 14% in these plants. Thus, the proposed model can minimize the impact on grid instability and the cost of energy consumption of an industrial customer. Some scenarios have been suggested in the study including the variation of the capacity factor, considering onsite electrical power generation such as solar power plants and waste heat recovery power plants, which can enhance the demand response obtained from the cement subsector.

Moreover, cement manufacturing is a highly energy-intensive process, with over half of the thermal energy used in the production chain being lost. Consequently, exploring ways to capture and utilize this wasted heat to generate electricity and meet industrial energy requirements is crucial. The study investigates the potential for Waste Heat Recovery (WHR) power generation within the Ethiopian cement industry. The levelized cost of energy (LCOE) and the Net Present Values (NPV) of the steam Rankine cycle-based, Organic Rankine cycle-based and Kalina Rankine cycle-based waste heat recovery power plant options are evaluated. The findings reveal that the steam Rankine cycle-based waste heat recovery power plant is the only feasible plant in the Ethiopian cement plant, with the net present value of 0.35 million USD, and about 0.04 USD per kWh of levelized cost of energy. The power capacity of the feasible plant is about 8.9 MW for the studied cement plant with an annual production capacity of 2.3 Mt of cement. This amount can cover roughly 18% of the case study cement plant's electricity demand.. The associated reduced CO_2 emissions potential is not significant, as the hydropower sources dominate the national power grid.

In summary, this doctoral research underscores the feasibility of adapting demand-side management (DSM) strategies in the cement industry. The main findings are compared with similar studies and international benchmarks, confirming the practical applicability. Detailed sensitivity analysis has been conducted to ensure that the results derived from the base case assumptions remain reliable despite potential fluctuations in the variations of influencing parameters. Consequently, this thesis can be a valuable resource for energy policymakers and industry players seeking to develop effective DSM strategies and policies. The methodologies and frameworks employed can be applied to similar energy-intensive sectors worldwide, aiding in formulating DSM strategies for the energy system.

Keywords: demand-side energy management, energy efficiency, demand response, onsite power generation, cement industry, benchmarking & energy saving tool, mixed integer nonlinear programming, energy conservation supply curve, waste heat recovery system, levelized cost of energy.

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Thank you,
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Publications

his PhD thesis is based on the following papers. All the papers are appended at the end of the thesis. The first two publications are journal articles, the third is a conference paper, and the fourth is a journal manuscript that has been submitted for publication.

Paper I **Mossie, A. T**., Wolde, M. G., Beyene, G. B., Palm, B., & Khatiwada, D. (2021). A comparative study of the energy and environmental performance of cement industries in Ethiopia and Sweden. *International Conference on Electrical, Computer, Communications and Mechatronics Engineering, ICECCME 2021*. https://doi.org/10.1109/ICECCME52200.2021.9591148

Paper II **Mossie, A. T**., Khatiwada, D., Palm, B., & Bekele, G. (2023). Investigating energy saving and climate mitigation potentials in cement production – A case study in Ethiopia. *Energy Conversion and Management - Journal*, *287*, 117111. https://doi.org/10.1016/J.ENCONMAN.2023.117111

Paper III **Mossie, A. T**., Khatiwada, D., Palm, B., & Bekele, G. (2025). Energy demand flexibility potential in cement industries: How does it contribute to energy supply security and environmental sustainability? *Applied Energy*, *377*, 124608. https://doi.org/10.1016/J.APENERGY.2024.124608

Paper IV **Mossie, A. T**., Khatiwada, D., Palm, B., & Bekele, G. (2024). Techno-economic analysis of waste heat recovery power plants in cement industry – a case study in Ethiopia. Under review at Next *Energy Journal.*

The author of this thesis is the main author of the papers. In those, the literature review and analysis, methodology and data analyses, as well as the writing of the papers were performed by the thesis author. All these contributions were conducted under the supervision and guidance of Dr. Dilip Khatiwada, Professor Björn Palm, and Dr Getachew Bekele.

Nomenclature

Acronyms

ECSC	Energy Conservation Supply Curve
CCE	Cost of Conserved Energy
EECSC	Electrical Energy Conservation Supply Curve
EEMs	Energy Efficiency Measures
EII	Energy Intensity Index
FCSC	Fuel Conservation Supply Curve
GHG	Greenhouse Gases
CF	Capacity Factor
MW	Megawatts
SSA	Sub-Saharan Africa
Bt	Billion tonnes
GJ	Gigajouls
GWh	Gigawatt hours
kt	Kilo tonnes
CO_2	Carbon dioxide
IPCC	Intergovernmental Panel on Climate Change
DSM	Demand Side Management
TJ	Terajoules
BEST- Cement	Benchmarking and Energy Saving Tool
DR	Demand Response
MINLP	Mixed Integer Nonlinear Programming
USD	United States Dollar
Mt	Million tonnes
kWh	kilowatt hours
MWh	Megawatt hours
IEA	International Energy Agency
EEP	Ethiopian Electric Power

SEC	Specific Energy Consumption
UNFCCC	United Nations Framework Convention on Climate Change
PJ	Petajoules
TOU	Time-of-use electricity price rate
EPRA	Energy and Petroleum Regulatory Authority
ERA	Electricity Regulatory Authority
URA	Rwanda Utilities Regulatory Authority
CEMBUREAU	European Cement Association
CC	Capital cost
LCC	Life cycle cost
LCOE	Levelized cost of energy
ORC	Organic Rankine cycle
REG	Revenue obtained from energy generation
KRC	Revenue obtained from energy generation
RC	Replacement cost
OMC	Operation and maintenance cost
NPV	Net present value
SV	Salvage value
SRC	Steam Rankine cycle
WFC	Working fuel cost
WHRPP	Waste heat recovery power plant

Symbols

i	the index of the cement plant
j	the index of the machine/loads at each cement plant
t	the index of the hour of the day
$p_{i,j,t}$	the amount of electrical load used by machine j of plant i during time t
V_{ave}	the average operating speed of the machine(s)
$P_{i,t}$	the total electrical load consumed by plant i at hour t
P_t	the total electrical load consumed by the whole plant during t hour
P^s	the average hourly electrical used by the whole plant at shoulder period

e_p	the hourly electricity price of the day's peak period
e_s	the hourly electricity price of the day's shoulder period
e_o	the hourly electricity price of the day's off-peak period
$\omega_{i,j}$	the hourly electrical energy used by machine j of plant i
e_s	the hourly electricity price of the day's shoulder period
e_o	the hourly electricity price of the day's off-peak period
$x_{i,j,t}$	binary variable showing the device j of factory i works or not during hour t
e_p	the hourly electricity price of the day's peak period
$\omega_{i,j}$	the hourly electrical energy used by machine j of plant i
$\mathrm{t_{oh}}$	the maximum operating hours of the sub-processing machines/loads
Q	annual production of semi-finished/finished products
P^o	the average hourly electrical used by the whole plant at off-peak period
$h_{i,j}$	the daily required time to operate equipment j of plant i
d_p	number of hours of the day in the peak period of the grid
d_s	number of hours of the day in the shoulder period of the grid
d_o	number of hours of the day in the off-peak period of the grid
C_{pi}	the average daily electricity cost of plant i
$\vec{c}_1$	the daily maximum amounts of the total electrical load of plant-i
$\tilde{c}_2$	the daily maximum amounts of total electrical load of machine–j of plant-i
P^p	the average hourly electrical used by the whole plant at peak period
$E_{daily\ flexible}$	the daily flexibility potential of the time-bounded process/load
A_y	annual running cost
E_y	annual electricity generation by the WHR power plant
y	lifetime of the plant
d	discount rate
r_M	annual incremental factor of operation & maintenance cost
r_F	annual fuel cost factor
r_s	annual equipment replacement cost factor
dr	annual depreciation rate

r_E	energy price factor
F_n	the net cash flow over the plant's lifetime
EG_{WHR}	annual electrical energy generated by the waste heat recovery power plant
ER_{co_2}	annual total CO_2 emission reduction
EF_{ele}	Electricity grid emission factor

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Chapter 1: Introduction

In this introductory chapter, background information is provided, encompassing the Ethiopian power system and the energy demand of the cement manufacturing process, outlined in section 1.1. The statement of the problem is depicted in section 1.2, followed by the research objectives, including key research questions in section 1.3. Section 1.4 presents the motivation of this thesis. Finally, the structure of the thesis is outlined in section 1.5.

1.1 Background

Securing access to clean and reliable energy sources is essential for a nation's socioeconomic growth, industrialization, and sustainable development (Risoli, 2021). The global energy landscape is undergoing significant changes, driven by rising energy demand, the quest for sustainability, and climate change challenges (Zohuri, 2023). According to a report by the International Energy Agency (IEA), global electricity demand grew at an average annual rate of 2.4 % between 2015 and 2019. Figure 1.1 shows that the industrial and residential sectors dominated electrical energy use, accounting for 42% and 27% of the total world electrical energy demand in 2019, respectively (IEA, 2022). On the other hand, energy costs constitute a significant portion of the total production expenses for most manufacturing industries (Mickovic & Wouters, 2020). These industries spend millions of dollars annually in electricity and fuel oil to meet their energy needs. The share of energy costs varies among industries, depending on factors such as energy efficiency, technology enhancements and raw material requirements (IEA, 2021c). For instance, in the cement industry, the average energy costs account for 30-40% of total production costs (IFC, 2017a). Similarly, in the steel and aluminum industries, the proportion of energy costs reach 20-40% (Kim et al., 2022) and 25-45% (Ndjebayi, 2017), respectively of the overall production cost. To improve economic competitiveness, these sectors are researching various mechanisms to increase energy efficiency and implement suitable energy management systems.

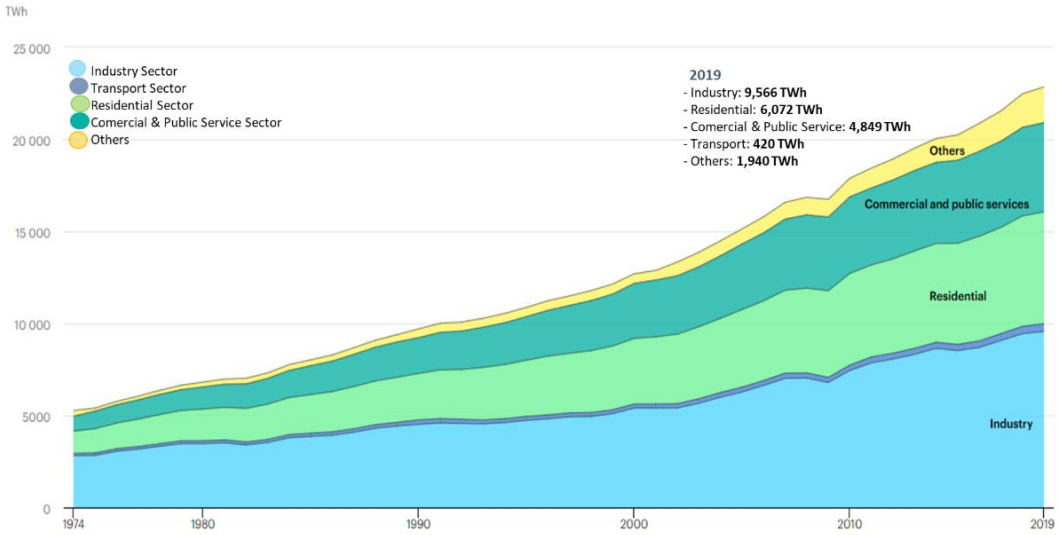

Figure 1.1: The world electrical energy demand in different sectors from 1974 to 2019 (IEA, 2022)

Moreover, the industry sector is responsible for about 23% of greenhouse gas emissions (EPA, 2023). These emissions primarily come from the combustion of fossil fuels for energy, and from certain chemical reactions necessary to produce goods from raw materials. When emissions from electricity use are allocated to the industrial end-use sector, the industrial sector's share increases substantially to around 30% of total greenhouse gas emissions. Globally, it is estimated that energy-related activities account for more than three-quarters of total greenhouse gas (IEA, 2023b). Hence, besides clean energy production, efficient demand-side energy management in the industrial sector can reduce carbon footprint and mitigate the environmental impacts associated with energy production and use. As one of the Sustainable Development Goals (SDGs), Goal 7, is targeting to ensure access to affordable, reliable, sustainable and modern energy for all by 2030 (*Home | Sustainable Development*, 2023), the need for innovative and efficient energy management strategies is becoming increasingly imperative.

1.1.1 Overview of the Ethiopian Power System

Based on data from Ethiopian Electric Power (EEP), the installed power generation capacity in the country reached 5,274 MW in 2022, with hydropower contributing approximately 90.7% of the total capacity (*Eep – Ethiopian Electric Power*, 2022). Wind and thermal sources account for 6.6% and 2% respectively, while biomass and geothermal sources contribute smaller percentages of 0.51% and 0.15%. However, with an actual total generation of 15,512 GWh in 2021, the per capita electricity consumption of the country is only about 100 kWh per year, much lower than the African average of 600 kWh per year (IEA, 2020). Hence, with a population exceeding 123 million people (The World Bank, 2022), Ethiopia is

facing challenges in meeting the increasing electricity demand, expected to grow by approximately 30% each year (*International Trade Administration*, 2022). As a result, load shedding is a common practice used to manage the electricity generation deficit in the grid. Consequently, power can shift from the industry to the household customer during peak hours, impacting both energy consumption and factory production efficiencies. Furthermore, power quality issues, such as frequent voltage fluctuations and power outages, are other challenges that hinder the operational efficiencies of the energy-intensive manufacturing industries in Ethiopia (Haile & Perumal, 2020). To address these challenges, it is essential to build new power plants and expand the electric grid to reach more customers. Simultaneously, it is also crucial to identify factors contributing to power system instability and inefficiency. Hydropower plants can serve as a storage mechanism for balancing fluctuating power sources. In Ethiopia, large reservoirs are generally used to generate electricity throughout the year (MOWE, 2022). The challenge, however, is that the current installed capacity of all power plants is insufficient to meet the national demand, particularly during peak hours. Diesel generators are usually energized to support the grid during this period, but this practice is neither economically nor environmentally feasible (Gebremeskel et al., 2021). Therefore, the effective adaptation of demand side energy management (DSM) strategies, particularly demand response (DR) strategy can greatly benefit a power system, especially in developing economies like Ethiopia, where supply constraints and reliability issues are common.

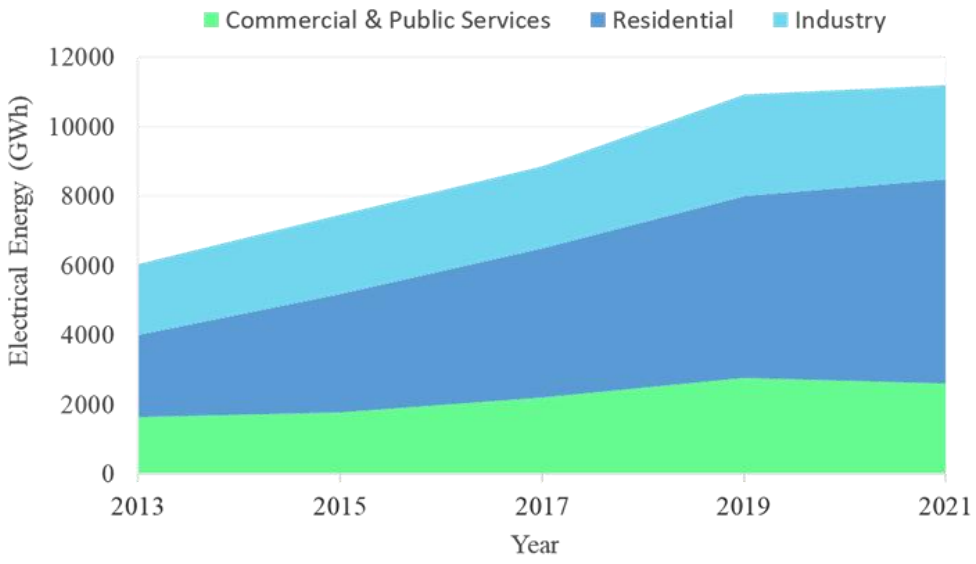

Figure 1.2: Annual electrical energy demand in Ethiopia (by sector)(IEA, 2020)

On the other hand, energy expenses constitute a substantial portion of the overall production costs in most manufacturing industries (Mickovic & Wouters, 2020). These industries allocate millions of dollars annually to cover their energy needs. Figure 1.2 shows that the demand for electrical energy in the Ethiopian industrial sector has been increasing annually, accounting for approximately 25% of the country's total electrical energy consumption in 2021 (IEA, 2020). Therefore, implementing demand-side energy management strategies can help the grid to match the demand, and effectively utilize the generated energy. In addition, electricity generation from other renewable energy sources such as wind and solar energy is getting more attention in Ethiopia, which is expected to play a significant role in meeting future demand. Hence, DSM strategies can also assist the grid in aligning the demand with the timely energy generation from these sources. Moreover, extensive work on managing industrial energy demand can benefit the industry in various ways. It can help to save money on energy bills, improve energy efficiency, maintain a sustainable environment and improve grid stability.

1.1.2 Electricity Price Tarff Structures in Ethiopia and East African Countries

The electricity tariff serves as a signal to customers indicating the cost of marginal consumption, and should ideally encourage the most effective use of existing capacity (Mburamatare et al., 2022). Costs in the power sector fluctuate based on factors like times of the day (peak/off-peak), seasons (dry/rainy), types of users (residential/industrial), and geographic areas (urban/rural). These factors should be taken into consideration when setting prices that promote efficient use. However, policymakers must balance the financial sustainability of the sector and social well-being while defining tariff structures (Briceño-Garmendia & Shkaratan, 2011). Despite the fact that utilities in regulated markets are currently supposed to adopt dynamic pricing models, governments, particularly in East African countries, are still providing significant subsidies to their customers, which can create operational inefficiencies in the sector. Nevertheless, some countries, such as Kenya, Uganda, and Rwanda have implemented timely varying pricing structures like TOU tariff rates in their respective power systems (Mburamatare et al., 2022).

Table 1.1: TOU tariff structures for some of the East African countries

Kenya, (EPRA, 2022)		Rwanda, (Rura, 2020)		Uganda, (*ERA*, 2021)	
Energy charge USD/ kWh	Remark	Max. demand charge (USD/kVA)	Remark	Energy charge (USD/kWh)[a]	Remark
Peak: 0.06 Off-peak: 0.03	For commercial & industrial consumers (66 kV)	Peak: 6.56 Shoulder: 1.83 Off-peak: 0.81	For large industrial users (>660 MWh/year)	Peak: 0.11 Shoulder: 0.09 Off-peak: 0.07	For extra-large industrial customers (11 kV, 33 kV), with at least 1500 kVA

The energy charge (cost/kWh) is based on the amount of electricity a consumer uses over some time, while the maximum demand charge (cost/kVA) is based on the highest level of electrical demand (load) a customer places on the power system at any point during the billing period. Both charges in the specified countries are components of TOU pricing schemes incentivizing customers to optimize their use. Costs are expressed in United States Dollar (USD) using average exchange rates from March 2023, as data were taken during that time.
[a] this TOU tariff scheme has only been applied to those industries with smart meters.
Table 1 shows only TOU price signal for large industrial customers for the three countries' power grids. However, the total tariff includes an energy charge, a maximum demand charge, and a customer service charge.

The authority in charge of electricity tariff setting in Kenya-the Energy and Petroleum Regulatory authority (EPRA) categorizes customers into different groups (EPRA, 2022). EPRA applies different TOU tariffs on the different categories of customers based on voltage levels, customer categories, and level of consumption. It also adjusts the tariff based on factors including fuel energy cost, foreign exchange rate fluctuation, inflation, security support facility, water levy, taxes and levies, and a power factor. Similarly, the Electricity Regulatory Authority (ERA) has the mandate to regulate the electricity industry in Uganda. ERA has different categories of customers, the TOU tariff structure is applied to commercial consumers, medium industrial consumers, large industrial consumers, and extra-large industrial consumers categories (*ERA*, 2021). The annual base tariff shall be adjusted at the beginning of each calendar year taking the changes in other tariff parameters such as energy losses, collection rates, operation and maintenance costs, investment costs, and macroeconomic factors such as exchange rate, inflation, US produce price index and international price of fuel into account. The macroeconomic parameters used in the determination of the annual base rate do not necessarily remain constant, and an adjustment factor might be required. Rwanda Utilities Regulatory Authority (RURA) executes the managerial functions of the national power utility (Rura, 2020). For small, medium and large industrial customers of the utility in Rwanda, flat rate is applied for all units (kWh) of electricity consumed for each category, and the rate differs based on their level of consumption, while the maximum demand charge (FRW/KVA/month) is based on the TOU structure as described in Table 1.1.

The electricity pricing scheme in Ethiopia is a flat rate structure with the same tariff for all hours of the day about 0.04 USD per kWh for high voltage customers, according to March 2023 data (*EEU Portal*, 2022). This tariff is among the lowest in Africa and is below the cost of electricity generation (NARUC, 2021). Accordingly, the Ethiopian Energy Authority is in the process of conducting a study to revise the existing tariff, considering a potential doubling of the current price to ensure sustainable profits (*Capital Newspaper*, 2021). Given that the current flat-rate scheme cannot incentivize demand-side energy management, the historical average of the East African countries' TOU price structures has been used in this study to show how cost-effective is the demand response application in the Ethiopian cement industry.

1.1.3 The Cement Manufacturing Sector

Cement is one of the most consumed construction materials in the world (Mulatu et al., 2018). The total cement production in 2020 was estimated at 4.1 Billion tonnes (Bt), of which China produced 2.2 Bt of cement, accounting for more than half of the global production; followed by India and Vietnam with the production of 340 and 96 Million tonnes (Mt) in the same year, respectively (US Geological Survey, 2021). The cement production share of Africa was 5.1% of the total world cement production in 2018, from which Nigeria, South Africa, and Ethiopia were the leading producers in the region as reported by the European Cement Association (CEMBUREAU, 2019). According to the US Geological Survey report, cement production is expected to increase from 4.1 Bt in 2020 to 4.86 Bt in 2030 (US Geological Survey, 2021). It is also projected to increase by 12-23% from the current level in 2050 (IEA, 2021c). As developing nations are more expected to develop their infrastructures, cement production is more likely to increase in these countries than in developed nations, as estimated by the International Energy Agency (IEA) (IEA, 2019).

1.1.3.1 Cement Manufacturing Process and Its Energy Demand

Cement is manufactured through a detailed production procedure that starts with extracting raw materials like limestone, chalk, shale, clay, and sand (IFC, 2017d). Figure 1.3 depicts the three primary phases of cement production: raw material preparation, pyro-processing and cement grinding (Worrell et al., 2013). In the first stage, raw materials are mined, crushed, and milled. Based on the specific type of cement being produced, these materials are mixed with specific additives such as iron ore and alumina to achieve the desired chemical composition, forming a fine powder known as raw meal. In the pyro-processing phase, the raw meal is fed into a cement kiln - a large rotating furnace where it is heated to around

1,450°C. this process removes moisture, decomposes carbonate compounds (calcination), and leads to the formation of cement minerals (clinkerization), resulting in the production of clinker, a hard, nodular substance. Finally, in the grinding phase, the clinker is cooled and milled together with gypsum and small amounts of other additives to produce final cement (IFC, 2017d), as illustrated in Figure 1.3.

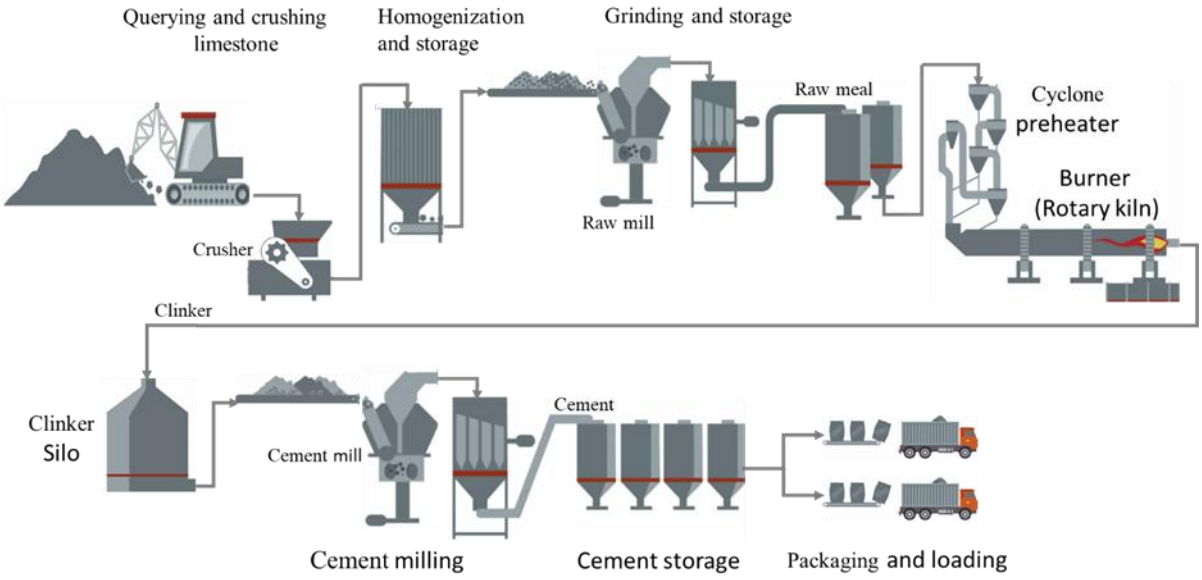

Figure 1.3: Main cement production processing stages, adapted from (IFC, 2017d), with graphics sourced from (VisionTIR, 2018)

The cement sector is estimated to account for approximately 7% of global industrial energy usage, highlighting its energy-intensive nature (IEA, 2021c). Various energy sources are employed throughout the cement production process, primarily in the form of electrical and thermal energy (Mossie et al., 2021). On average, producing one tonne of cement in a dry-process plant requires 110 kWh of electricity and 3.4 GJ of thermal energy, though this may vary based on the technology used and the composition of raw materials (Mokhtar & Nasooti, 2020). Most of the thermal energy, about 93–99%, is consumed within the kiln. Meanwhile, electricity usage is distributed across three key phases: cement grinding (38%), raw material processing (33%), and pyro-processing (22%). Consequently, energy expenses in this sector are significant, accounting for approximately 30–40% of total production costs (Worrell et al., 2013).

The sector is responsible for significant amounts of greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), nitrogen oxide (NO_2) and carbon monoxide (CO) (Ali et al.,

2015). These emissions mainly originate from fuel combustion and the calcination process (Ali et al., 2015). The quantity of emissions is primarily influenced by the type of energy source, the clinker-to-cement ratio, and the raw materials utilized (Thakuri et al., 2021). Carbon dioxide emissions from fuel burning and electricity usage constitute nearly 50% of the total CO_2 emissions associated with global cement manufacturing (Hasanbeigi, Menke, & Price, 2010). The average CO_2 emissions from cement manufacturing range between 0.73 and 0.99 tonnes of CO_2 per tonne of cement, primarily influenced by the clinker-to-cement ratio, along with other factors like energy source and raw material composition (Mokhtar & Nasooti, 2020). As per the Global Cement and Concrete Association, the cement sector was responsible for approximately 7% of worldwide CO_2 emissions in 2020 (GCCA, 2021).

Given the high energy demand and substantial CO_2 emissions in cement manufacturing, exploring sector-specific strategies is essential to enhance energy efficiency in the sector. In the energy-intensive industry, it is well established that upgrading from low-efficiency to high-efficiency technologies can significantly impact performance and energy usage, potentially leading to lower production costs (Afkhami et al., 2015). Nevertheless, this approach necessitates identifying viable energy-efficient technologies while assessing their effects on energy savings, emission reductions, and economic feasibility in cement production. Consequently, the study seeks to analyze energy and emission performance while assessing the cost-effectiveness of energy-saving technologies and approaches within the cement sector.

1.1.3.2 Cement Production in Ethiopia

Ethiopia stands as a prominent cement producer in Africa, boasting a production capacity of over 13 Mt per year in 2017 (IFC, 2017b), which reached 19.7 Mt per year by 2021 (Asoko Insight, 2023). According to a report from the Ethiopian Ministry of Industry, the country has a high demand for cement due to rapid urbanization (4.3% rate) and high population growth (2.6% rate), together with a substantial need for infrastructure development and execution of forthcoming mega projects (GoE, 2013). In addition, cement producers in Ethiopia continue to expand the capacity of their existing plants and construct new ones, exemplified by the Lemi National Cement Factory project, which is expected to be completed by March 2024 with a targeted production capacity of 4.5 Mt of cement per year (East African Holding, 2024). The cement industries in Ethiopia are comprised of both local and international companies and are concentrated around the capital, Addis Ababa, where over 40% of the plants are located (Asoko Insight, 2023). Despite its substantial production potential, the

industry only utilized around half of its capacity by 2020 due to challenges, such as limited access to machinery spare parts, foreign exchange, and electricity (Mossie et al., 2023) (Asoko Insight, 2023). As of 2020, there were about 20 cement plants in the country (Mulatu et al., 2018), with major players including Dangote Cement, Derba Cement, Mugher Cement, Messebo Cement, Habesha Cement, and National Cement with annual production capacities ranging from 1.2 to 2.5 Mt (See Figure 1.4). As presented in the figure, these plants collectively contributed to about 88% of the country's annual cement production in 2020 (GoE, 2013).

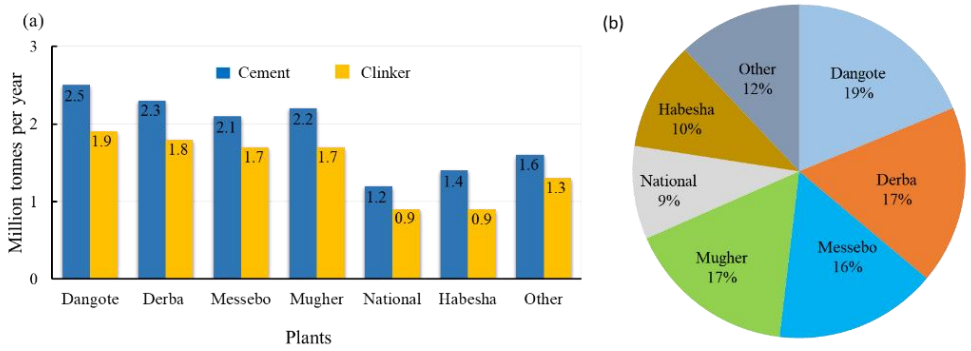

Figure 1.4: (a) Installed cement production capacity, (b) Production share of major cement plants

As already mentioned, cement production is an energy and emission-intensive industry; however, the energy and environmental performances of the Ethiopian cement plants have not been evaluated so far taking their specific energy use, technologies applied, and process types into consideration. Thus, in this study, the Ethiopian cement plants have been considered as a case study to investigate the energy saving and CO_2 emission reduction potentials by implementing effective energy efficiency technologies and measures, and to assess the energy demand flexibility potential in cement industries.

1.2 Statement of the Problem

As generated electrical energy cannot be stored in a power system (Iberdrola, 2023), a power grid is designed in such a way that the supply and demand of electrical energy has to be continually balanced (Gan et al., 2020). Consequently, the grid is responsible for delivering electricity to the ever-increasing demand by the respective customers through supply-side energy management options (Grunewald & Diakonova, 2018). This task has become increasingly challenging due to high fluctuations in electricity demand and increasing penetration of intermittent renewable energy into the electricity supply mix (Sharifi et al.,

2019). The impact on power grid stability becomes more significant with higher electrical energy demand or load in specific industries, posing potential challenges to grid stability (Roesch et al., 2019). This phenomenon is more pronounced in a country like Ethiopia where access to electricity reaches still less than half of its population (IEA, 2021b). Despite significant advancements in electrification programs, substantial portion of the country's residents still lack access to electricity. Hence, the country is facing energy shortages to serve a population of more than 123 million people (The World Bank, 2022) and meet growing electricity demand, which is expected to grow by approximately 30% each year (*International Trade Administration*, 2022). Power quality problems including frequent voltage fluctuations and power outages are other challenges to the power system network and to the operation efficiencies of the energy-intensive manufacturing industries (Haile & Perumal, 2020). In other words, it is necessary to build new power plants and expand the electric grid towards new customers, at the same time, it is also necessary to identify the causes that make the system unstable and inefficient. By focusing on energy management, demand side energy management, energy utilization assessment and efficiency improvement, introduction of new technologies: significant results can be achieved; saving money on energy bills, improving energy efficiency and maintaining sustainable environment, improving grid stability, etc. Moreover, demand-side energy management can also contribute to achieving one of the Sustainable Development Goals (SDGs), Goal 7, which targets to ensure access to affordable, reliable, sustainable, and modern energy for all (*Home | Sustainable Development*, 2023)

Renewable energy resources like wind and solar are anticipated to be widely deployed in the power system network. However, a significant challenge associated with these resources is their uncertain characteristics, which implies that energy generation is not as per the necessities of demand request rather it is as per the availability of resources (Diaz-gonzalez, 2020). This phenomenon leads the grid to generate electricity from its conventional power plants during peak demand, rendering it economically and environmentally inefficient. Thus, supply-side flexibility is not economically and environmentally friendly in this regard. While integrating energy storage into the grid whenever required can be one option, concerns persist regarding its capacity to effectively balance supply-demand deficiencies (Roesch et al., 2019). Conversely, the power grid needs to become carbon neutral, and the share of Variable Renewable Energy Sources (VRES) in the energy mix should increase (ENTSO-E, 2022), while the demand should cope with the variable energy supply. Thus, in addressing this

challenge, demand-side energy management emerges as potential solution to the problem faced in the modern power grid (Rombouts et al., 2021).

1.3 Research Objectives

The primary objective of this PhD study is to propose optimal energy utilization strategy for energy-intensive industries, with a particular focus on the cement industries in Ethiopia. The aim is to minimize their impact on the national power grid and simultaneously reduce their specific energy consumption, energy-related costs, and associated CO_2 emissions.

The specific objectives of the study include the following:

- Assessing the energy and environmental performances of the Ethiopian cement industry (RO1)
- Investigating energy saving and climate mitigation potentials in cement production (RO2)
- Assessing and developing demand flexibility energy optimization model suitable for the cement industry (RO3)
- Evaluating the techno-economic feasibility of waste heat recovery power plant for the case of the Ethiopian cement industry (RO4)

1.3.1 The Research Questions

The main research question of the study:

How can industrial demand-side energy management strategies be effectively adapted to optimize energy usage, reduce costs, and enhance sustainability in the energy system?

The following specific research questions have been addressed in this study:

Under research RO1: Assessing the energy and environmental performances of the Ethiopian cement industry

- How does the energy and environmental performance of the Ethiopian cement industry be compared against international benchmarks and best practices?
- What is the estimated potential for improving energy efficiency in the Ethiopian cement sector?

Under research RO2: Investigating energy saving and climate mitigation potentials in cement production

- How can the energy conservation supply curve model be developed to prioritize the potential energy efficiency-enhancing measures and technologies based on their cost-effectiveness and technical feasibility for a typical cement industry?
- What are the cost-effective energy saving and CO_2 emission reduction potentials of the investigated measures?

Under RO3: Assessing and developing demand flexibility energy optimization model suitable for the cement industry

- How much energy demand flexibility can be expected from selected industries?
- How can an energy consumption optimization model be developed, considering demand response potential in the cement industry?
- How does energy demand flexibility contribute to energy supply security and environmental sustainability?
- To what extent do policy and regulatory frameworks influence the success of demand-side energy management initiatives?

Under RO4: Evaluating the techno-economic feasibility of waste heat recovery power plant for the case of Ethiopian cement industry

- Which heat recovery power generation technology options are technically and economically viable for the Ethiopian cement industry?
- What percentage of the energy demand can be met by the feasible onsite power plant?

1.4 Motivation of the Study

The motivation for this study stems from the increasing challenges associated with meeting the growing energy demands while striving for sustainability. The challenges faced in the modern power grid to match the ever increasing energy demand with the intermittent energy resources cannot be addressed by only supply side energy management. Rather energy management in the demand side, specifically on energy intensive industries remains a crucial and dynamic component. The need to optimize energy consumption, reduce environmental impact, and enhance overall energy efficiency is paramount. This study seeks to address these challenges by delving into the complexities of demand-side energy management, aiming to provide actionable insights for a more sustainable and resilient energy future.

As the demand side is increasingly recognized as a crucial element in achieving grid reliability, energy efficiency, and sustainability, this doctoral study has made substantial

contribution in advancing energy stakeholders' understanding of demand-side energy management strategies. The research has primarily focused on investigating measures and technologies for enhancing energy and environment efficiency, assessing onsite power generation potential, and developing demand response strategies tailored to the cement industry within the Ethiopian context. By addressing these needs in one of the most energy-intensive sectors, the study plays significant role in enhancing energy efficiency and sustainability, benefiting not only the cement industry but also the broader energy landscape. This research also suggests policy recommendations aimed at promoting sustainable and flexible energy usage in the energy-intensive industry and forwards valuable insights for the design and implementation of effective demand-side management practices and policies. Ultimately, it contributes to the development of a more resilient and sustainable energy system within the Ethiopian power grid.

1.5 Thesis Structures

In the thesis, the state-of-the-art of demand-side energy management is presented in Chapter 2, with a detailed explanation of energy efficiency, demand response, and onsite power generation with special focus on the industrial sector. The potential energy efficiency measures and technologies, demand response programs & techniques and practices of onsite power generation potential are demonstrated with the context of energy-intensive industry. Chapter 3 outlines the materials and methods applied in this study. It demonstrates the procedures for assessing the energy and environmental performances of the examined cement plants, along with methods for comparing and benchmarking against industry best practices. this chapter includes the techniques and approaches for analyzing energy efficiency-enhancing measures and technologies using an energy conservation supply curve model, as well as assessing the potential and developing an energy optimization model for demand flexibility in the cement sector are derived. Moreover, the procedures and methodologies to analysis the techno-economic viability of waste heat recovery power generation are developed in this chapter. The main findings of the study are presented in Chapter 4, encompassing the assessments of energy and environmental performances of the Ethiopian cement industry, along with benchmarking and comparison analysis with best practices. The details investigation of cement-specific energy efficiency-enhancing potential for energy saving and climate mitigation, are presented. The case study results for the energy demand flexibility potential in the cement industry are also reported in this chapter. Furthermore, Chapter 4 presents the techno-economic evaluations of waste heat recovery power plants for the case of

the Ethiopian cement industry. In Chapter 5, discussions are centered on the key findings of the study, including the comparison of the main findings of the study with related studies and international references, further reflections, and scenario analysis on the demand response and WHR power generation potential in the cement industry as well as insights on policy implications on demand-side energy management in the energy-intensive industry. Finally, the key conclusions and the way forward are expressed in Chapter 6.

Chapter 2: Demand-Side Energy Management (DSM) - Literature Review

In this chapter, the state of the arts of demand-side energy management strategies are presented with detailed literature reviews, incorporating the three categories of DSM. Demand Response (DR) programs and techniques are explained in section 2.1. Section 2.2 discusses measures and practices to enhance energy efficiency in energy-intensive industrial sectors, focusing on energy efficiency and climate mitigation technologies in the cement industry. Section 2.3 describes onsite power generation potential in industrial facilities, particularly within in the cement industry. Finally, section 2.4 highlights the scientific novelty and research contributions of the study.

Demand-side energy management commonly known as Demand-Side Management (DSM) is an intelligent management of electrical energy demand (Dahiru et al., 2023). The activities that can alter the magnitude and/or time of use of power in order to enhance the overall economic benefits of the customer and the power grid can be categorized as DSM (Arteconi & Bruninx, 2018). In other words, DSM refers to the practice of managing electrical loads to enhance demand flexibility and lower costs (Bakare et al., 2023). It has been proven to be an effective approach to increase the power grid performance and customer benefits. Thus, the application of DSM measures in energy-intensive industries like cement, steel and aluminum can play an important role in reducing energy costs. Moreover, it can play crucial role in maintaining the balance between electricity supply and demand on a power grid, thereby enhancing overall grid stability (Golmohamadi, 2022). Figure 2.1 illustrates three key approaches to achieve DSM objectives in the industrial context: Energy Efficiency (EE), on-site power generation and Demand Response (DR) (CPower, 2024) (Zhang & Grossmann, 2016).

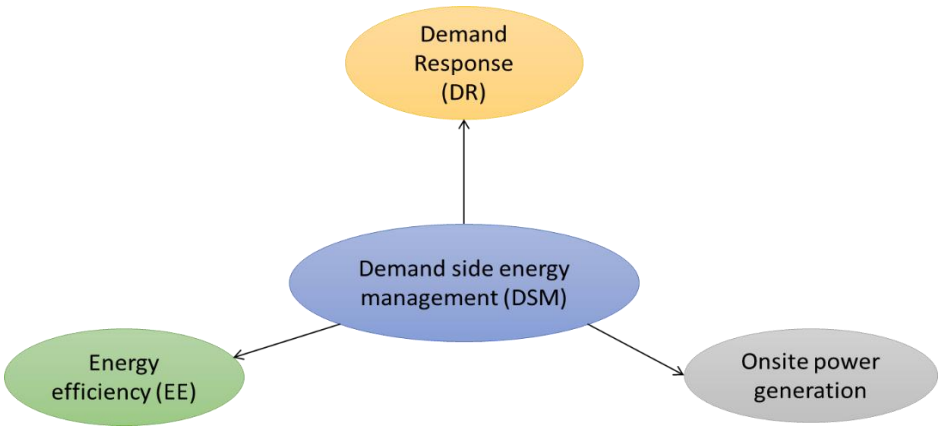

Figure 2.1: demand-side energy management categories

2.1 Demand Response (DR)

Demand response refers to the adjustment of customers' load profile in response to an external event (Policy, 2015). The US Federal Energy Regulatory Commission (FERC) defines demand response as 'changes in electrical energy usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized' (FERC, 2010). It aims to balance the demand on the power grids by encouraging customers to curtail or shift their energy consumption to times when electricity supply is more abundant or demand is lower (IEA, 2023a). The demand flexibility provided by customers is therefore referred to as demand-side flexibility or simply demand response (Golmohamadi, 2022). In the industrial sector, a review of the literature suggests that cement, steel, and aluminum plants have a large demand flexibility potential (Hassan H. Alhelou, Antonio Moreno-Muñoz, 2022). DR can also help reduce the need for fossil power plants during peak times, contributing to a lower greenhouse gas emissions and a cleaner environment (Utilities One, 2023). Thus, in the boarder context, DR is a valuable tool to modernize the electrical power grid, enhance energy efficiency, and promote a more sustainable energy future (Energy5, 2024).

2.1.1 Demand Response Programs

Different DR strategies can be applied in the energy sector to manage and balance the electricity demand in response to supply condition, grid reliability or price signals, through optimizing the use of electricity by encouraging customers to adjust their consumption during peak periods, or in times of grid stress. Energy intensive industrial facilities, which require a huge electricity consumption to produce goods and services, are ideal candidates for participating in this kind of strategies, reducing their operating cost while making the grid more stable and secure (Pablos et al., 2021). These strategies can be broadly divided into two groups: Incentive-based (Program options) and Price-based (tariff options) (Morales-España et al., 2022) (refer to Figure 2.2). Incentive-based DR are stability-based DR programs in which customers are asked to participate in DR actions when events occur that affect system reliability. In this case, consumers are paid for not consuming energy in response to the grid operator's request. In both cases, consumers are encouraged to be flexible in the face of high demand and/or shortage on the supply side. Direct load control program, interruptible program, demand bidding program, emergency DR program, capacity market program, and

axillary service program are under incentive-based program options which are often based on economic incentives which are not included in the electricity rates (W. Y. Chen et al., 2016). Under direct load control program, utilities control certain loads of the participant customers, compensating them in return. In interruptible/curtailable load programs, participants are asked to decrease their load to predetermined levels. Failure to respond may result in penalties based on program terms and conditions (Jabir et al., 2018). Both direct load control and interruptible/curtailable load programs fall under classical incentive-based DR programs, where participants receive compensation, usually as a bill credit or discount rate, for their involvement. In market-based programs, participants are rewarded for their performance, depending on the amount of load reduction during critical conditions. Demand bidding programs customers biding on specific load reductions in the electricity wholesale market. When the bid is accepted, the customer must curtail its load by the amount specified in the bid or face penalties. Emergency DR programs offer incentives to participating customers for measured load reductions during emergency conditions (Pallonetto et al., 2020). Moreover, capacity market programs are offered to customers committing to pre-specified load reductions during system contingencies. Participants receive advance notice of events and are penalized if they do not respond to calls for load reduction. Ancillary services market programs allow customers to bid on load curtailment in the spot market as operating reserve, often for short period of time. If the bids is accepted, participants will be paid the spot market price for committing to be on standby and for load curtailment (Jabir et al., 2018).

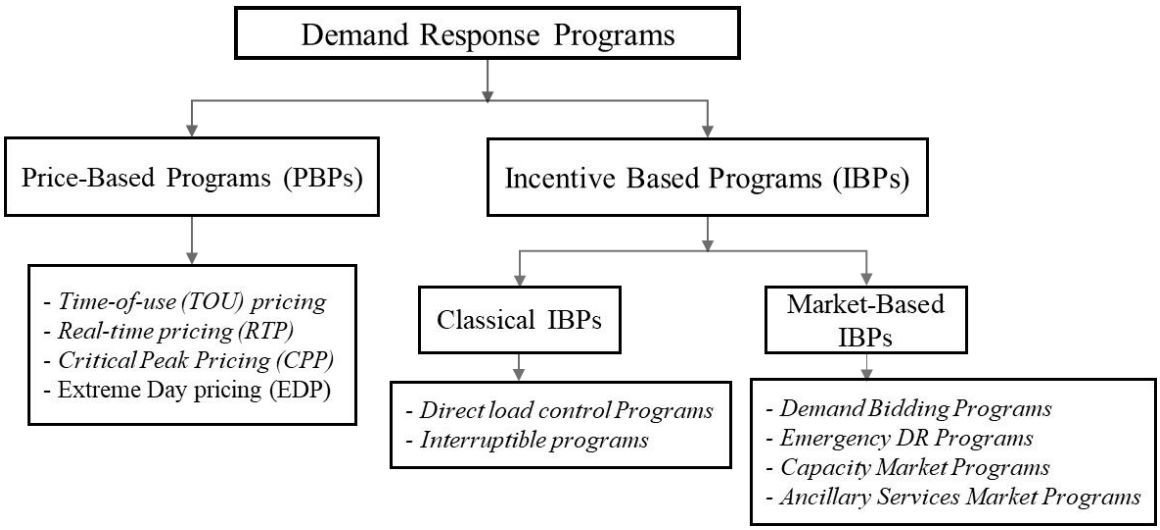

Figure 2.2: Classification of demand response programs

Price-based DR options, on the other hand, are market-driven DR programs that respond to wholesale electricity price signals (Merkert et al., 2015). These options are market options for

customers that can make a profit by reducing their energy consumption during peak periods. The customer can take advantage of periods of lower prices and avoid consumption during periods of higher electricity prices. Time of use (TOU), Real time pricing (RTP) and Critical peak pricing (CPP) are under this program with the goal of reducing the electricity demand variance by increasing the price signal on high peak demand and reducing it at low peak (Derakhshan et al., 2016). The basic type of PBP is the TOU rates, which are the rates of electricity price per unit consumption that differ in different blocks of time, but remains consistent from day to day. The simplest TOU rate has two time blocks; the peak and the off-peak, aiming to reflect the average cost of electricity during these periods (Albadi & El-Saadany, 2008). While RTP programs involve customers to charge hourly with fluctuating prices reflecting the actual electricity cost in the wholesale market which varies daily. RTP customers receive price information on a day or an hour-ahead (Electric, 2022). Economists advocate for RTP programs are the most direct and efficient demand response programs suitable for competitive electricity markets and should be the focus of policymakers (Mburamatare et al., 2022). CPP program rates include an additional pre-specified higher electricity usage price superimposed on TOU or normal flat rates. This pricing strategy can improve power system as it reflect the system state. Hence, if appropriate critical peak pricing signals are disseminated, consumers may respond by reducing their load during system-stress events (Jabir et al., 2018). A detailed time varying pricing scheme design is outlined in (Mburamatare et al., 2022).

2.1.2 Demand Response Techniques

The general DR techniques used by customers can be categorized as peak clipping (load curtailment), load shifting, valley filling, strategic conservation, flexible load shape and strategic load growth, or a combination of these techniques (see Figure 2.3) (Bakare et al., 2023); these actions can be applied in response to the DR programs of the utilities (Sharifi et al., 2019). Demand response technique that is aimed at decreasing consumption during peak times can be categorized as peak clipping (load curtailment). Load shifting is mostly associated with usage reduction at the peak which is offset by usage in off-peak hours. Consumers may shift the operation of certain energy-intensive appliances or processes to periods of the day when electricity demand is lower, typically during off-peak hours or when renewable energy generation is abundant. DR technique that focuses on increasing electricity consumption during periods of low demand, often during nighttime hours when the overall grid load is lower, or

at times with high renewable energy production can be categorized as valley filling (Eid et al., 2016).

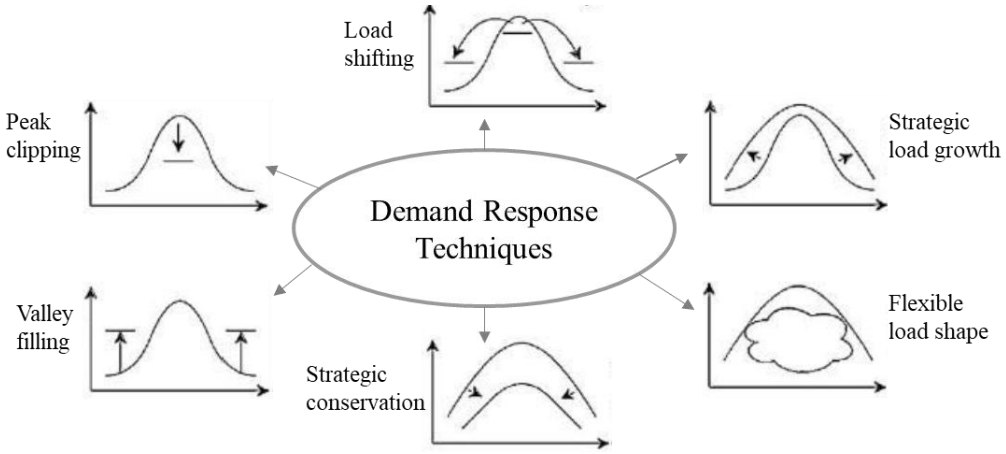

Figure 2.3: Demand response techniques adapted from (Bakare et al., 2023)

Strategic conservation involves implementing energy-saving measures during critical times to reduce overall electricity demand. Consumers can deploy energy-efficient technologies, turn off non-essential equipment, or adjust building temperatures during peak demand periods to strategically conserve energy (Bakare et al., 2023). Flexible load shaping technique involves optimizing the pattern of electricity consumption to match grid conditions and price signals. Consumers with flexible loads can adjust their energy consumption according to the DR programs, and can be benefited from it and contribute to the grid stability. Strategic load growth refers to the planning and management of increasing electricity demand in a manner that aligns with grid capabilities and overall system objectives (Ullah et al., 2023). Utilities and industries can strategically plan for electricity demand growth by integrating new loads to improve grid stability, incorporates renewable energy sources, and minimizes the need for additional infrastructure. Thus, implementing a combination of these techniques can enhance the effectiveness of demand response programs, and helps to balance supply and demand while improving overall efficiency and reliability.

2.2 Energy Efficiency in Energy-Intensive Industries

Energy efficiency refers to the optimization of energy utilization to achieve desired outcomes while minimizing input or energy waste (European Environment Agency, 2023). Its objective is to reduce energy consumption and waste, thereby enhancing sustainability, reducing environmental impact, and often leading to cost savings. The goal of implementing energy efficiency measures in industrial facilities, such as cement, aluminum, iron, and steel industries, is to reduce energy losses and greenhouse gas emissions (GHG) in the sector (IEA,

2021a). This aims to promote more sustainable energy consumption patterns while maintaining production targets through the application of energy-efficient measures, technologies, practices, and related efficiency improvement approaches (Mossie et al., 2023).

2.2.1 Energy efficiency and climate mitigation Measures/technologies in cement industries

Several studies have been conducted to evaluate energy efficiency and greenhouse gas (GHG) emission mitigation in cement production. The International Finance Corporation (IFC, 2017d) compiled international best practices, primarily focusing on specific technical Energy Efficiency Measures (EEMs) that cement plants can adopt to lower their energy consumption and GHG emissions. It outlined a set of strategies for key stages of cement production, including raw material preparation, clinker production and cooling, fuel processing, and final grinding, along with general facility-wide measures. These EEMs were detailed in terms of capital and operational costs, cost-effectiveness, and implementation considerations. Similarly, (Worrell et al., 2013) examined potential energy efficiency-enhancing measures, assessing their benefits in terms of energy savings and CO_2 emission reductions while also analyzing related costs such as investment and operation and maintenance expenses. The study also highlighted global experiences from cement plants, demonstrating the significant potential for energy efficiency improvements within the sector.

According to the IEA (IEA, 2021c), one of the most effective strategies for mitigating CO_2 emissions- in the cement industry is enhancing energy efficiency by adopting state-of-the-art technologies and measures. Among the key energy-saving innovations examined are high-pressure grinding rolls and vertical roller mills, which could theoretically reduce electricity consumption by up to 50% and 70%, respectively, compared to traditional ball mills. The report also highlights upgraded process controls and the use of variable speed drives as additional measures for improving electricity efficiency. In the pyro-processing stage, the most efficient technologies identified include dry-process kilns equipped with a pre-calciner, pre-heater multistage cyclones, and multichannel burners. The report emphasizes that successful implementation of these energy-saving measures requires collaborative efforts from various stakeholders, including government and industry. (Cantini, Leoni, Carlo, et al., 2021) listed energy-efficient measures by dividing them into two groups: process-stage measures and machine-type measures. In this paper, a compulsory energy audit conducted in the Italian cement industry identified cost-effective solutions such as installing inverters on compressors, pumps, and fans, as well as incorporating heat recovery systems and variable-

speed drives. A study by the United Nations Industrial Development Organization (UNIDO, 2014) further classified the best available technologies in the cement sector into low-, medium-, and high-cost energy efficiency measures, depending on investment requirements. High-cost technologies included a heat recovery system for electricity generation, upgrading older dry kilns to multi-stage pre-heater and pre-calciner kilns, and using roller mills for coal grinding. In contrast, low-cost measures involved process control for vertical mills, enhanced energy management systems, and optimized heat recovery solutions. (Wang et al., 2022) assessed deploying a waste heat recovery system as a practical solution for electricity generation, reducing dependence on costly external energy, and improving decarbonization through full utilization of exhaust heat. Similarly, (Talaei et al., 2019) analyzed the long-term potential for greenhouse gas reduction in the Canadian cement industry. this work examined 10 globally recognized energy efficiency options using scenario analysis, classifying them into three categories based on economic feasibility: economically attractive, cost-neutral, and high-cost measures. While fuel switching and alternative raw material usage were considered nearly cost-neutral, energy management systems and heat recovery were found to offer the most cost-effective carbon savings.

Thus, the literature suggests numerous strategies for conserving energy and lowering CO_2 emissions in the cement industry. However, the practicality and cost-effectiveness of these measures largely depend on the specific energy consumption patterns of the plant. Therefore, this doctoral study conducts a comprehensive assessment of potential energy efficiency measures (EEMs) within the Ethiopian cement industry, offering valuable insights into achievable energy savings and emission reductions.

2.3 On-Site Power Generation in Industrial Facilities

On-site power generation in industrial facilities refers to the generation of electricity or heat at the location where it is consumed, rather than relying solely on power from the grid. Much like energy efficiency initiatives and DR techniques, on-site power generation can benefit both the user and the grid in various ways including improved reliability, energy cost savings, and support sustainability (CPower, 2024). The implementation of on-site power generation in the industrial settings such as solar power plants, wind power plants, waste heat recovery power plants and diesel generators serves to reduce dependence on the grid (CEMBUREAU, 2022). The technological advancement of small-scale power plants has further progressed, with several innovative technologies attaining grid parity (Schulz et al., 2021). On the other

hand, as an emissions-intensive sector, manufacturing companies have been challenged to deliver environmental friendly products to their customer (Umweltbundesamt, 2020). Therefore, the integration of small-scale power generation plants at their own site represents a promising strategy, not only ensuring technical independence from the electricity grid but also enabling sustainable product delivery. The paper (Schulz et al., 2021) outlines that in an exemplary manufacturing company, located in the metalworking sector of Germany with an electricity demand of approximately 20,000 MWh/a, a promising energy cost reduction of almost 20 has been achieved through a maximum expansion of photovoltaic (PV) systems and the utilization of combined heat and power (CHP) to cover the base load. The technical and economic feasibility of on-site renewable energy production from solar and wind for a specific manufacturing plant, the pharmaceutical company, in Ireland, is assessed in (Sgobba & Meskell, 2019). The study analysis considers the impact of technical and economic input parameters on the Net Present Value (NPV). In light of this study, although there is a technical potential for on-site renewable energy generation, the economic conditions required to make it a feasible option for the manufacturing industry in Ireland are deemed challenging. Specifically, factors such as a reduction in the initial investment cost, substantial subsidies, and an extended payback period are necessary.

2.3.1 On-Site Power Generation Potential in Cement Sector

Potential renewable energy sources such as wind farms and solar power plants can be assumed to be used in cement production to ensure the power supply in case of grid instability (Atlas Renewable Energy, 2023). However, waste heat recovery power generation is the most common practice in the cement industry. Normally the waste heat released from the kiln is used to dry raw materials or other materials like coal, petcoke, or cement constituents. It can also be partially recovered to produce electricity through a waste heat recovery power generation plant. Depending on the type of plant technology (steam, ammonia or organic-based process), between 8 and 22 kWh/tonne of clinker, or up to 16% of the power consumption of a cement plant can be produced by using these technologies without altering the kiln operation (CEMBUREAU, 2022). According to the International Finance Corporation (IFC) report (IFC, 2014), Waste Heat Recovery Technology (WHR) utilizes residual heat in the exhaust gases generated in the cement manufacturing process and can provide low-temperature heating or generate up to 30% of the plant electricity needs. The report also identifies the main factors that can influence the WHR technology viabilities such as production capacity of the cement plant, moisture content of the raw materials, the design

of pre-heating stages, the reliability of the electrical power supply, and industrial electricity tariffs.

Cement manufacturing is a highly energy-intensive process, with over half of the thermal energy used in the production chain being lost. As summarized in Table 2.1, the major heat loss in cement production occurs through pre-heater exhaust gas and clinker cooler gas. According to (Naeimi et al., 2019), about 22.5% and 14.1% of the input heat wasted through preheater exhaust gas and clinker cooler gas from a five-stage preheater and pre-calciner kiln of 3541 tonnes of clinker per day capacity. In (Ghalandari, 2022), 20% and 15% of the input heat losses through them from a 5-stage pre-heater and pre-calciner kiln with 227 tonne-per-hour production capacity. The input energy losses through different sections in a typical dry-processed cement plant have been summarized in the Table. Raw material combustion occurs within the kiln system, by taking the prepared raw meal, fuel, and air. The resulting clinker, a product of the heated raw meal, is discharged, accompanied by significant heat. This portion of heat that remains uncaptured will be released into the atmosphere as waste. Hence, WHR power plants are essential components of energy efficiency strategies in the cement industry, where significant amounts of heat are generated as a byproduct of various processes.

Table 2.1: Thermal energy efficiency of a typical cement plant with primary areas of energy losses (literature review)

Losses through (%)	(Naeimi et al., 2019)	(Mohammed Bin Qadhi & Abdul Raheem Bawazir, 2013)	(Verma et al., 2021)	(Nivethidha Priyadarshini & Sivakumar, 2014)	(Ghalandari, 2022)	Average
Pre-heater exhaust gas	22.5	21.6	14.9	24.4	20	20.7
Clinker cooler hot gas	14.1	7.3	12.5	12.8	14.9	12.3
Sub-total losses	36.6	28.9	27.4	37.2	34.9	33
Clinker discharge	3.7	2.9	3.18	2.7	2.9	3.1
Dust & moisture	3	1.1	0.4	2.5	1.7	1.7
Radiation & convection	6.1	6.4	4.5	6.1	-	5.8
Other losses	3.2	1	5.74	-	-	3.3
Thermal efficiency	47.4%	59.7%	58.7%	51.5%	60.5%	55.6%
Kiln type	five stage pre-heater	Multi-stage Pre-heater	six-stage pre-heater	four-stage pre-heater	five-stage preheater	
Kiln capacity	3400 t/day[a]	4000 t/day	9700 t/day	3018 t/day	227 t/hr[b]	
Country (case study)	Iran	Yemen	India	India	Iran	

[a] t/day: tonnes per day, [b] t/hr: tonnes per hour

(Mohammed Bin Qadhi & Abdul Raheem Bawazir, 2013) conduct a detailed energy audit on the clinker-making section of a case study plant (with 4000 ton/day production capacity), applicable to dry process cement plants. According to the energy balance result obtained, the kiln's thermal efficiency is found to be 59.7%, with major heat losses in the preheater exhaust gas (22%) and clinker cooler air (7.6%). Then, possible ways of heat recovery from the major sources of heat loss were discussed and proposes a conventional Waste Heat Recovery Power Generation (WHRPG) system, recovering approximately 7.5 MW (13.3% of total plant power input) via a steam Rankin cycle, or 9.75 MW with a Kalina Rankin cycle. The cost and the payback period of the two models are also calculated. (Naeimi et al., 2019) explores waste heat recovery electrical power generation at Tehran cement factory, considering two approaches. The first comprises a single heat recovery steam generator (boiler) to recover waste heat from exhaust gases and hot air from the clinker cooler. the second involves two recovery boilers, with exhaust gases from the preheater enters the preheater HRSG, and hot air from the cooler goes in the cooler HRSG, then the steam produced by each HRSG mixed together in the mixing chamber and turns the steam turbine-generator to produce power. Results show that the first scenario recovers 23931 kJ/s with an efficiency of 23.5%, while the second recovers 21253 kJ/s with an efficiency of 22.2%. The comparison suggests the single recovery boiler system is more effective in power production. (IFC, 2018) assesses the status and untapped potential of WHRPGs in the Turkish cement industry. By the end of 2016, 10 cement plants were operating WHRPG with a total production capacity of 100.7 MW, in addition, there were four cement plants in the process of developing WHRPs with 34 MW capacity. The report underscores several benefits of WHRPGs, including decreased reliance on captive power plants, resilience against future electricity price hikes, improved power reliability, reduced grid energy consumption, and lower greenhouse gas emissions. From these studies, we can conclude that the technical and economic feasibilities of WHRPPs are site and country specific.

2.4 Scientific Novelty and Research Contributions of the Study

As can be seen in the reviewed literature, despite the significant impact of industrial loads on power grid instability, most demand-side flexibility-related studies including, (Dranka & Ferreira, 2019), (Sharifi et al., 2018), (Sharifi et al., 2017) have investigated DR potential based on residential customers, which typically have different characteristics from industrial loads (Morales-España et al., 2022). However, some studies address the demand response capabilities of industrial facilities. (Lu et al., 2021) proposes a data-driven real-time pricing-

based DR algorithm for industrial facilities to minimize electricity costs. Similarly, (X. Huang et al., 2017) offers real-time pricing-based DR opportunities for electricity customers using an artificial neural network price forecasting model. Both papers conduct case studies on steel power manufacturing plants to test the effectiveness of their schemes in balancing energy demand and reducing costs. Another study (Rodríguez-García et al., 2016) uses a process-based simulation tool to analyze the cost-benefit of DR activities in industrial customers and to mitigate the impact of RES intermittency on the power grid. In this paper, the authors evaluate the technical, economic, and environmental aspects of DR potential in the selected facility. To validate the introduced approach, the paper used a paper factory in Germany, two meat factories in the Netherlands and Spain, as well as a logistics warehouse for food products in Spain. (Pierri et al., 2020) develops an integrated approach to demand flexibility strategies specifically for the process industry in Germany, providing essential requirements for investment decisions in the sector. This study demonstrates that integrating energy-oriented production planning and utilizing energy management tools improves energy efficiency and flexibility at the plant level. These studies formulate industrial energy management problems based on real-time prices (RTP), which can be predicted in advance to some extent. However, this approach requires bidirectional communication technologies such as smart meters and surveillance systems between grid operators and customers as a prerequisite for smart grid infrastructure (Bektas, Z., Kayakutlu, G., Kayalica, 2018). (Roesch et al., 2019) proposes an end-to-end approach connecting machines with markets through IT platforms to fully utilize industrial demand flexibility. The paper integrates multilevel optimization to encompass the necessary processes and design an energy synchronization platform for industrial customers using a Business Process Model and Notation (BPMN) approach. (Summerbell et al., 2017) indicates that demand-side energy management, particularly production rescheduling based on electricity price variations, benefits both industrial customers and electricity suppliers. The study shows that load shifting can be achieved through production rescheduling by adapting machine configurations in selected units of the plants.

On the other hand, there are power grids that do not have bidirectional communication technologies and use flat rate or TOU pricing schemes which are pre-determined pricing structures (Mburamatare et al., 2022). As explained by (Kholerdi & Ghasemi-Marzbali, 2021), in the TOU tariff structure, the peak, shoulder, and off-peak hours of the day with their electricity unit prices have been determined by the utility. Customers are then expected to

adjust their energy consumption according to the TOU pricing in order to reduce their energy costs.. (Bektas, Z., Kayakutlu, G., Kayalica, 2018) develops a DR model for a power grid with a single electricity-generating center aimed at smoothening load flows and reducing grid instability. This study proposes the model for paper, detergent and hygienic products factories; however, the objective function should be developed with consideration for the cost-effectiveness of reducing energy usage during peak hours and increasing energy usage during off-peak hours. The reduction in energy consumption during peak periods leads to a corresponding decrease in factory production. Nevertheless, this particular study does not tackle this aspect. Though (Dewangan et al., 2022) aims to decrease electricity costs and peak-to-average demand ratio for TOU tariff users, it does not promote increased off-peak period energy consumption in the intraday load distribution. While these works evaluate the DR potentials of users, they do not address the detailed industrial DR potential for a power grid that does not have smart grid features.

As highlighted in the literature review, previous research has explored demand response (DR) potential across different consumer categories. Most of these studies have developed DR optimization models based on real-time pricing (RTP) by predicting in advance while requiring a smart grid infrastructure. However, some power utilities, including the Ethiopian Electric Utility, lack this technological capability. Several studies have instead developed industrial DR optimization models using predetermined time-of-use (TOU) pricing schemes. However, these models primarily focus on cost reduction rather than effectively minimizing electricity demand during peak periods. Additionally, some research has evaluated the cost-effectiveness of load reduction strategies during peak hours but without integrating energy consumption and production planning considerations. Consequently, the specific objective of this PhD study is to bridge these gaps by developing a model that combines energy consumption optimization with detailed production scheduling to fully assess the potential of industrial DR in conventional power grids. The proposed DR optimization model is designed to reduce the loads of a cement plant during peak periods without compromising the daily production target while lowering the associated production costs.

On the other category of DSM, Energy Efficiency (EE), several studies have assessed potential energy-efficient measures and technologies through a bottom-up Energy Conservation Supply Curve (ECSC) model. This widely recognized analytical tool demonstrates the energy-saving potential based on the marginal cost of the energy saved

(Fleiter et al., 2009). Zuberi and Patel (Zuberi & Patel, 2017) applied this model to evaluate the Swiss cement industry's energy savings and CO_2 reduction potential. Their findings indicated that in 2014, the sector achieved a14% energy demand savings along with a 13% total CO_2 emissions. Similarly, (Hasanbeigi et al., 2011) evaluated forty-seven EEMs in Thai cement sector using ECSC model and identified cost-effective electricity savings of 8% and fuel savings of 16%. However, these studies did not consider the specific performance of cement plants from the best practice perspective. This limitation could lead to misconceptions among stakeholders and policymakers, potentially affecting the effective implementation of energy efficiency measures (EEMs).

(Y. H. Huang & Wu, 2021) examined energy savings and CO_2 reduction potential in the Taiwanese cement industry for 2018 using the ECSC model. paper estimated an annual energy savings potential of 5.98% and CO_2 emission reduction of 3.88%, with 51.2% of electricity savings and 92.5% of fuel savings being cost-effective. (Njoku et al., 2017) analyzed three Nigerian cement plants incorporating 17 potential energy-saving measures. The findings indicated that a dry-process cement plant had the potential to save 374,055 GJ of energy annually through cost-effective EEMs.

Similarly, (Morrow et al., 2014) investigated 22 energy efficiency-enhancing measures in the Indian cement sector, estimating cost-effective electrical energy savings of 83 TWh, which led to a CO_2 emission reduction of 82 Mt. The study also analyzed the measures that could achieve cumulative cost-effective fuel savings of 1,029 PJ resulting in a CO_2 reduction of 97 Mt from 2010 to 2030. (Hasanbeigi, Price, et al., 2010) examined thirty-four energy-efficient technologies and measures across 16 cement plants in China, identifying cost-effective electricity and fuel savings potentials of 16% and 8%, respectively, of the total energy consumption in 2008. These studies assessed cement plant performance by benchmarking individual plant efficiency against that of the most energy-efficient facility. The potential measures were examined using the ECSC model; nonetheless, the sensitivity of critical model parameters was not taken into account. Factors like the discount rate, capital cost, and energy unit price change over time and across different contexts, significantly impacting the study's outcomes. Thus, the cost-effectiveness of energy efficiency measures in the cement industry is influenced by the sensitivity of these key parameters, a factor that previous studies have overlooked. Moreover, there have been few studies conducted on the energy performance of the Ethiopian cement industry, despite the importance of energy costs and environmental

concerns in this energy-intensive sector. Previous studies have focused on reviewing the production, available resources (Mulatu et al., 2018), and energy consumption of the industry (Tesema & Worrell, 2015), but did not examine the environmental performance or assess potential energy efficiency measures with sensitivity analysis. Thus, no comprehensive research has been conducted to evaluate the potential for energy saving and CO_2 emissions reduction in the cement industry by integrating energy and emission performance, and cost-effective energy efficiency measures (EEMs) together with sensitivity analysis.

Thus, one of the specific objectives of this doctoral research targets to bridge this gap by assessing the energy consumption and CO_2 emissions of cement plants using a robust benchmarking tool. The potential energy-efficient technologies and measures are examined through the ECSC model which incorporates a broad range of key parameters to ensure more accurate results. Hence, this study is unique to Ethiopia, offering a comprehensive analysis of opportunities to enhance energy efficiency and mitigate CO_2 emissions in the cement sector. The findings can serve as a valuable reference for estimating potential energy savings and CO_2 reductions in Ethiopia's industrial sector. Furthermore, this study can be used as a benchmark for other countries seeking to evaluate and implement technologies and measures that enhance energy efficiency in their respective energy-intensive industries.

As discussed in Section 2.3, waste heat recovery systems (WHRS) are a viable option for onsite power generation in the cement sector, helping to reduce electricity grid dependency and associated emissions. Unlike intermittent renewable energy sources, WHRS can continuously generate power as long as the cement plant is running (CMA, 2021). This provides a reliable source of power that contributes to grid stability. Additionally, WHRS can be integrated into existing cement manufacturing technology with necessary modifications. However, it is important to consider the technical and economic feasibility specific to each cement plant and country when evaluating WHRS as an onsite power generation option in the cement industry.

In Ethiopia’s cement industry, the electricity needed is entirely dependent on the national power grid. However, cement industry releases significant amount of waste heat, which not only contributes to its energy inefficiency but also serves as a major source of emissions. Unfortunately, there has been a lack of sufficient attention given to exploring waste heat recovery systems within the Ethiopian cement sector until now. Nevertheless, (Ayu et al., 2015) conducted an energy audit and modeled a heat recovery system for a specific cement

plant in Ethiopia with a capacity of 3000 tons per day. Meanwhile, (Mossie, 2016) assessed the possible energy losses in another Ethiopian cement plant as a case study. However, neither of these studies explored the different waste heat recovery technology options for potential electricity generation within the Ethiopian cement industry. Therefore, the last objective of this study analyzes the viable waste heat recovery technology options for potential onsite power generation in the Ethiopian cement industry, aiming to improve overall energy efficiency and reduce associated CO_2 emissions in cement production, as well as to ensure stable power supply during grid instability, particularly during peak periods.

Chapter 3: Materials and Methods

This chapter provides a detailed description of the methodologies and materials utilized throughout the study. Section 3.1 outlines the overreaching approach and research design. In the following Section 3.2, the metrics for energy analysis and benchmarking are delineated. The methodology to estimate and develop energy demand flexibility potential within the cement industry is then presented in consecutive sections 3.3 and 3.4. Section 3.4 includes a mathematical optimization problem model to assess the viability of demand response (DR) in an energy-intensive industry. The system's configuration and metrics used to investigate techno-economic analysis of the waste heat recovery power plants in the cement industry are detailed in Section 3.5. Finally, Section 3.6 provides a comprehensive summary of the industry survey, datasets, and analysis used in the overall study.

3.1 General Approach and Research Design

Limited data is available regarding the energy utilization and environmental impact of cement production in sub-Saharan African countries, although a few studies suggest that the region exhibits relatively low energy intensity compared to global benchmarks. As Ethiopia's cement industry is a significant component of Sub-Saharan Africa's cement production with 20 large and medium-sized operational cement plants (see Chapter 1, section 1.1), monitoring energy performance and related CO_2 intensity of cement plants is the initial step in understanding the potential for improvement. By benchmarking against best practices with key performance indicators, opportunities for energy saving and emission mitigation are identified in the Ethiopian cement sector. This serves as a basis for developing Demand-Side Management (DSM) approaches to optimize energy management within the sector. Given its status as the most electricity-intensive sector, effective energy management not only benefits individual plants but also contributes to the overall stability of the power grid. DSM strategies encompass investigating energy efficiency potential, developing energy optimization models, & harnessing demand flexibility, and analyzing onsite power generation potential to reduce energy costs while enhancing grid stability and environmental sustainability, as the general research framework is depicted in Figure 3.1.

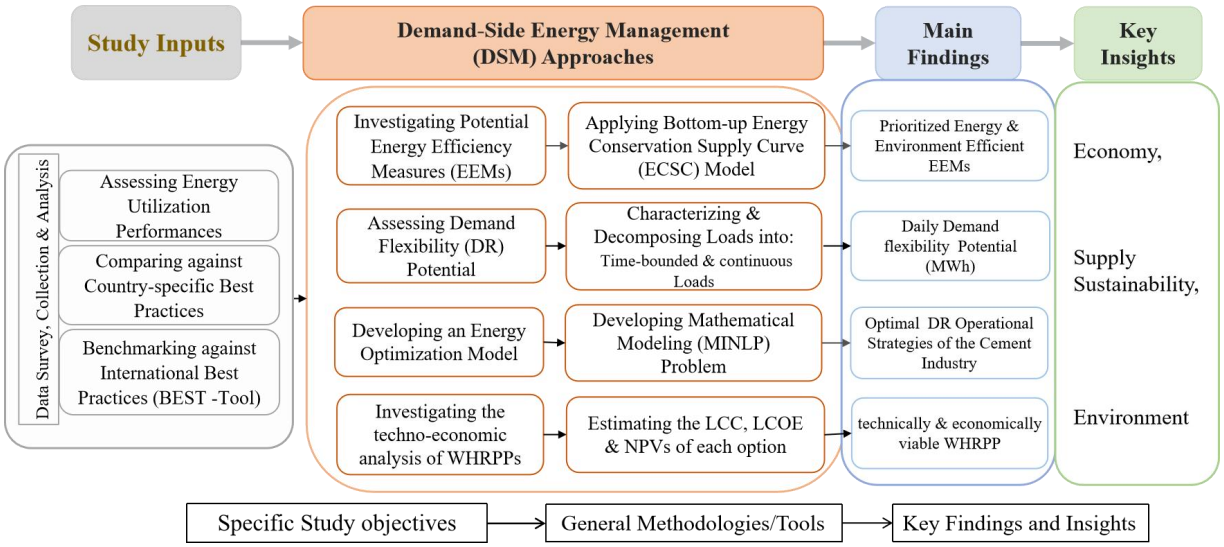

Figure 3.1: Workflow and Methodology of the study

3.2 Procedures for Assessing and Comparing Energy Utilization Performances

Evaluating and comparing the energy and environmental performances of the Ethiopian cement industry against best practices is crucial for identifying areas of improvement. This process involves analyzing factors such as energy usage, emissions, and environmental impact with established standards and industry norms. By benchmarking against leading practices, the Ethiopian cement industry can pinpoint areas where it excels and areas where enhancements are needed to align with global standards. This comparative analysis serves as a foundation for implementing strategies to enhance energy efficiency, reduce emissions, and promote environmental sustainability within the sector.

3.2.1 Comparing against Country-Specific Best Practices

To have a better understanding of energy utilization patterns in Ethiopian cement plants, the practices of the main Ethiopian cement plants were examined. The necessary data have been collected mainly to estimate the thermal and electrical energy performance, type of fuel, energy cost and utilization trend, product type, production technology, and volume. The collected data were processed to obtain key comparison parameters such as specific energy consumption, CO_2 intensity, clinker-cement ratio, and alternative fuel substitute (refer to section 3.6). After assessing the energy utilization of the Ethiopian cement industry, a brief review of the Swedish cement industry has been conducted to highlight the energy and environmental practices in both countries, followed by comparative analysis.

Heidelberg Materials Cement Sverige (formerly Cementa) is the sole producer of cement in Sweden, with two plants located at Slite (island of the southeast coast) and Skövde in

southern Sweden (Heidelberg Materials, 2024) (Mossie et al., 2021). It is one of Europe's front-runner cement industries striving for net zero-emission cement production by 2045 (Cementa, 2018). To achieve its mission, the Swedish cement industry has identified several alternative pathways that are crucial for climate-neutral cement production, including improved energy efficiency, substitution of fossil fuels, utilization of blended cement and/or clinker substitution, and integration of carbon capture and storage technology (CCS) as depicted in Figure 3.2. Significant strides have already been made within the Swedish industry regarding energy efficiency measures and the substitution of alternative fuels. Moreover, there is an ongoing project, the CemZero project, to develop a technology for electric heating of clinker production with ambitions for widespread implementation by 2030 (Vattenfall, 2020). Therefore, it could be essential for the Ethiopian cement sector to compare and leverage these opportunities from a leading industry in order to achieve energy and environmentally-efficient production.

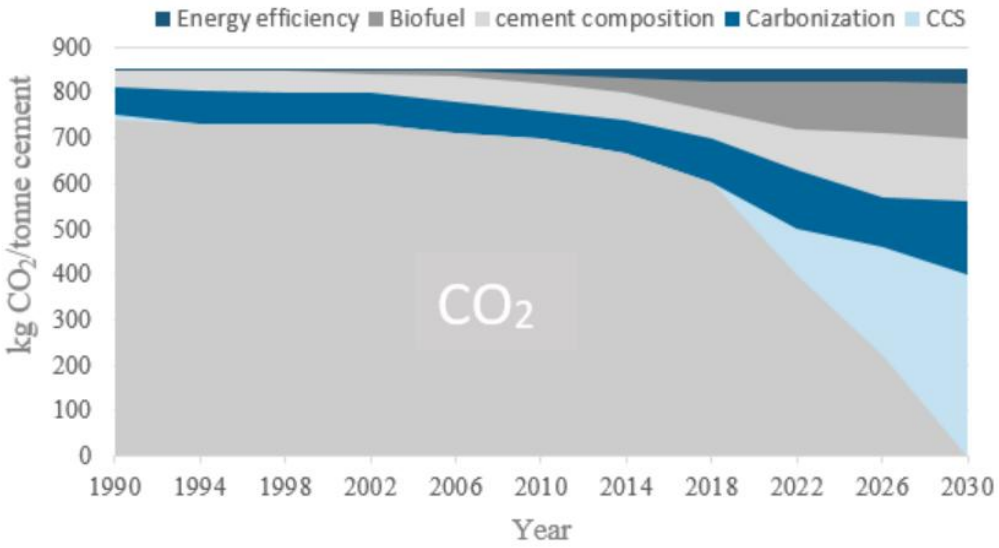

Figure 3.2: Swedish cement industry roadmap for reaching climate-neutral cement, adapted from (Cementa, 2018)

In this section, the methodologies employed encompass literature reviews, interviews, on-site data collection, and consultations with industry experts and researchers to source necessary information from country-specific practices, in particular with Sweden's cement industry. Key performance indicators are then collected and compared with those of the Ethiopian cement industry to furnish comparative insights and potential recommendations. In Ethiopia, data is gleaned from five of the largest cement plants (LCPs), which collectively account for approximately 78% of the nation's total installed production capacity in 2020. The data is meticulously analyzed to obtain key performance indicators, such as specific energy

consumption, emission intensity, the proportion of alternative fuels utilized, and clinker substitution rates. With a brief review of the Ethiopian and Swedish cement industries, this section presents the energy and environmental performance of the industries in both countries and provides a comparative analysis, followed by discussion and recommendations.

3.2.2 Benchmark the energy performance against international best practices – BEST Tool

The basic idea of energy benchmarking is to evaluate and compare the energy efficiency of two systems, which can range from entire industrial sectors to specific industrial process steps. A reference or benchmark system is essential for energy benchmarking to identify potential areas for improving energy efficiency. The primary goal is to pinpoint inefficiencies in energy use, potential energy savings, and enhance energy efficiency based on industry best practices. (Ke et al., 2013). Therefore, the studied cement plants are benchmarked against the most energy-efficient cement plant model using a robust benchmarking tool called Benchmarking and Energy Saving Tool (BEST-Cement) (Galitsky et al., 2008). It is a process-based tool used to develop a benchmarking cement plant model based on the available best practice technologies/measures for the major cement manufacturing process (Ke et al., 2013). The analysis of benchmarking has been done based on the Energy Intensity Index (EII) calculated for each plant. Depending on the data and input variables, the tool models a benchmark facility similar with the user's cement plant, but it is the most energy-efficient facility. The benchmarks defined in the BEST software set reasonable standards by which to compare plants that are striving to improve their energy efficiencies (Hasanbeigi, Price, et al., 2010).

3.2.2.1 Energy Intensity Index

The benchmarking tool computes the primary energy intensity index (EII) by considering the energy intensity, production output, and the energy intensity of the benchmark model for each examined cement plant. It then contrasts the overall production energy intensity of the individual cement plant/facility with that of the benchmark model (Hasanbeigi, Price, et al., 2010). The EII can be calculated by equation (3.1).

$$EII = \frac{\sum_{i=1}^{n} P_i * EI_i}{\sum_{i=1}^{n} P_i * EI_{iBM}} * 100 = \frac{EI_{it}}{\sum_{i=1}^{n} P_i * EI_{iBM}} * 100 \quad (3.1)$$

where,

- EII: energy intensity index
- n: number of products to be aggregated.
- EI_i: energy intensity for the product i of a typical cement plant facility (GJ/tonne)
- EI_{iBM}: energy intensity for product i of a benchmarking model (GJ/tonne)

- P_i: production quantity for product i (tonne)
- E_{it}: total actual energy consumption for all products (GJ)

The EII serves as a basis for estimating the potential energy savings of the analyzed plant. This is achieved by comparing the actual energy intensity of the cement plant with the intensity that would be attained if the plant were equipped with the most energy-efficient measures/technologies for each manufacturing stage or overall plant operations. The disparity between the actual energy intensity (energy consumed per tonne of cement produced) and the reference facility's energy intensity is computed for each key process within the plant and then aggregated for the entire plant. According to equation (3.1), a plant employing the best available energy efficiency measures/technologies would yield an EII of 100. However, actual cement plants typically have EIIs greater than 100. Hence, the gap between the EII of an actual plant and the EII of the reference facility represents the technical energy efficiency potential of the plant (Hasanbeigi, Price, et al., 2010). Moreover, the tool facilitates the assessment of energy efficiency enhancement potential by presenting a range of Energy Efficiency Measures (EEMs), along with their typical energy savings, associated CO_2 emission reductions, and capital costs for each measure (Galitsky et al., 2008).

3.3 Analyzing Energy Efficiency Opportunities in the Cement Industry

To examine feasible energy efficiency measures specific to the cement industry, potential EEMs are evaluated using the bottom-up energy conservation supply curves (ECSC) model. This model serves as a systematic tool capable of encompassing both the technical and economic aspects of energy conservation associated with the selected energy efficiency measures (Hasanbeigi et al., 2011). In addition, a comprehensive sensitivity analysis is performed, considering key parameters such as discount rates, energy unit prices, and capital costs of the measures employed in the model (Hasanbeigi, Menke, & Price, 2010). In order to apply this model, it is essential to identify potential EEMs suitable for the selected cement plants. In identifying those EEMs, the Industrial Efficiency Technology Database (Institute for Industrial Productivity, 2022), the Cement Technology Roadmap report by the IEA (IEA, 2021c), the reference documents prepared by the European Commission (2013) on BAT for the production of cement (Schorcht et al., 2013) and “Guidebook for Using the Tool BEST Cement: Benchmarking and Energy Savings Tool for the Cement Industry”, published by (Galitsky et al., 2008), and other related studies have been referred.

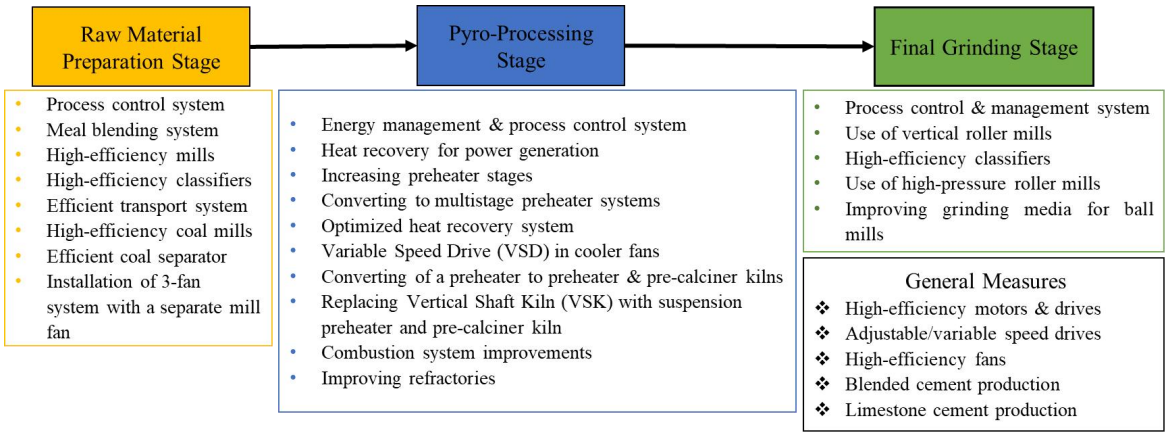

Figure 3.3: Selected cement specific Energy-Efficiency Measures (EEMs), compiled from (IEA, 2021c)(Galitsky et al., 2008)(Institute for Industrial Productivity, 2022)(Schorcht et al., 2013)

Each stage of the cement production process necessitates different processes and equipment and therefore requires distinct types of EEMs. Figure 3.3 illustrates the selected EEMs specific to the main processing stages of the surveyed cement plants. For the raw material preparation stage, some of the listed measures include the automation of the process control system, implementation of a raw meal blending system, utilization of high-efficiency roller mills, installation of high-efficiency separators & classifiers, and implementation of an efficient transport system. Moving to the clinker-making stage, the identified EEMs encompass energy management & process control, adoption of waste heat recovery for power generation, utilization of high-efficiency fans for pre-heaters, integration of pre-calciner & pre-heater to kilns, implementation of variable frequency drives for clinker cooler fans, and deployment of high-efficiency grate coolers. In the cement grinding stage, measures such as process control & management, adoption of high-efficiency vertical roller mills, and optimization of the cement mill operation, are listed. In addition, general measures, such as the utilization of high-efficiency motors & drives, and implementation of adjustable/variable speed drives are also included. The details of these EEMs are available in (IEA, 2021c)(Galitsky et al., 2008)(Institute for Industrial Productivity, 2022)(Schorcht et al., 2013).

3.3.1 Developing Energy Conservation Supply Curves

To evaluate the cost-effectiveness and the technical potential of the EEMs, including their energy savings and CO_2 emission reduction at the chosen cement plants, the energy conservation supply curve (ECSC) model is developed. This curve illustrates the energy conservation potential as a function of the marginal cost of conserved energy. The ECSC model has been used in various studies to assess energy efficiency potentials across different sectors (Hasanbeigi, Menke, & Therdyothin, 2010). It can be developed for individual plants,

a group of plants, an entire industry, or even the entire economic sector (Fleiter et al., 2009). Consequently, for the selected Ethiopian cement industries, unique and detailed energy efficiency improvement opportunities are identified and developed.

The Cost of Conserved Energy (CCE) required for constructing the ECSC can be determined using equation (3.2) (Hasanbeigi, Menke, & Therdyothin, 2010).

$$CCE = \frac{ACC + A\Delta O\&M}{\text{Annual Energy Savings}} = \frac{(\text{Net Present Values of Annual Costs})}{\text{Annual Energy Savings}} \quad (3.2)$$

where,

- ACC: Annualized Capital Costs
- CCE: Cost of Conserved Energy
- AΔO&M: Change of Annual Operation & Maintenance Cost

The annualized capital cost as a function of the discount rate (d) and life time (n) of the measure/technology can be calculated based on equation (3.3) (Hasanbeigi, Menke, & Therdyothin, 2010).

$$ACC = \text{Capital Cost} * \frac{d}{(1-(1+d)^{-n})} \quad (3.3)$$

where,

- n: lifetime year of the energy measure
- d: discount rate

To calculate the Annualized Capital Cost (ACC), it's necessary to define the discount rate (d) and the lifetime period (n) of the measure/technology being assessed. Lifetime period depends on the characteristics of the measures/technologies considered. For this study, the lifetime period of the selected measures is assumed to be 20 years (Hasanbeigi, Price, et al., 2010). The discount rate reflects the investor's risk preference and the cost of capital. In general, the discount rate varies from a low of 8% to a high of 30%. In this analysis, a discount rate of 30% is considered for the base case, which is commonly used for developing countries due to factors such as high inflation rates and investment risks (Hasanbeigi et al., 2011). The specific energy-saving potentials, associated CO_2 emission reductions, and required capital costs of the Energy Efficiency Measures (EEMs) are obtained from the Industrial Efficiency Technology Database and the BEST-Cement tool user manual. Once the cost of conserved energy (CCE) for all electrical energy and fuel efficiency measures included in the study is calculated, they are ranked in ascending order of their ACC to construct the Electrical Energy Conservation Supply Curve (EECSC) and Fuel Conservation Supply Curve (FCSC),

respectively. An energy price line, reflecting the current unit price of energy, is then determined on the ECSC. EEMs falling below this line are considered cost-effective. In the ECSC curve, the horizontal axis represents the energy saved by each measure, while the vertical axis represents the CCE per unit of energy saved. Thus, the ECSC provides the potential energy savings of the included EEMs in the study (Hasanbeigi, Menke, & Therdyothin, 2010). Cost-effective electrical energy and fuel efficiency measures/technologies are prioritized based on these criteria and can be recommended to cement plants and stakeholders for further consideration.

3.3.2 Emission Estimation Method

The total carbon dioxide (CO_2) emissions released from cement production, encompassing emissions from the calcination process, energy/fuel inputs (for heat production), and electricity consumption, can be determined using equation (3.4) (Thakuri et al., 2021).

$$\text{Total } CO_2 \text{ emission} = CO_2 \text{ emission}_{\text{Process}} + CO_2 \text{ emission}_{\text{Fuel Combustion}} + CO_2 \text{ emission}_{\text{Electricty Use}} \quad (3.4)$$

The CO_2 emissions resulting from fuel combustion and electricity use can be calculated by:

$$\begin{aligned} &CO_2 \text{ emission (due to fuel combustion and electricity)} \\ &= (\text{Energy/fuel inputs for heat [GJ]} * \text{Emission factor per fuel burnt [kg}CO_2\text{/GJ]}) \\ &+ (\text{electricalenergyrequirement[kW}h\text{]} * \text{Emissionfactor[kg}CO_2\text{/kWh](grid electricity)} \end{aligned} \quad (3.5)$$

The CO_2 emissions attributed to the calcination process occur primarily during material decomposition, particularly in the clinker burning phase. As per the Intergovernmental Panel on Climate Change (IPCC) methodology (tier 2 method) (IPCC, 2006), the CO_2 emissions from the calcination process can be determined using:

$$CO_2 \text{ emission}_{\text{Process}} = M_{cl} * EF_{cl} * CF_{ckd} \quad (3.6)$$

where,

- M_{cl} = Mass of clinker produced (Mt)
- EF_{cl} = emission factor for clinker (Mt CO_2/Mt clinker)
- CF_{ckd} = emission correction factor for cement kiln dust, CKD

As per the IPCC guideline, emission correction factor for clinker including CKD correction (EF_{clc}) is about 0.52 Mt CO_2/Mt clinker.

3.4 Assessing and Modeling Demand Flexibility Potential

The formulation of DR strategies within an industry should align with the planning and operation of power systems (dos Santos et al., 2023). As outlined in Figure 3.4, to model the aggregate demand flexibility of the cement industry, the loads of cement plants are categorized into controllable and non-controllable loads. Controllable loads are those that can be subject to Demand Response (DR) programs (Zhang & Grossmann, 2016). Depending on factors, such as specific energy consumption (SEC), operating speed and daily load hours, controllable loads can be further segmented into appropriate DR techniques taking into account the production targets of the plants (Rombouts et al., 2021). This process leads to the determination of the daily demand flexibility potential of the aggregated cement plants. Subsequently, by analyzing the hourly national power demand pattern; peak, shoulder (normal) & off-peak periods of the day are identified, including peak, average and base power demands. Accordingly, using these time intervals, along with the average TOU price rates of East African countries, and the controllable industrial load characteristics, a Mixed Integer Nonlinear programming (MINLP) model is proposed to obtain an optimal operational DR strategy in the cement plant.

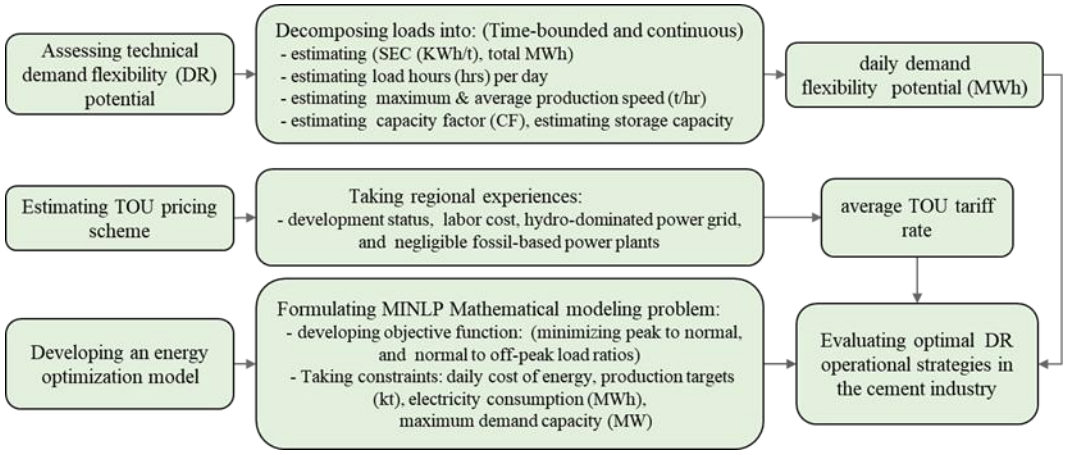

Figure 3.4: Methods/approaches used to develop the model

3.4.1 Estimating DR Potential in the Ethiopian Cement Industry

The cement production process occurs sequentially; it is not necessarily required to run all stages continuously for 24 hours a day as storage capacities are available for semi-finished/finished products (Olsen, 2012). As noted by S.P. Deolalkar (2009), most subsections within the process are designed to operate for specific durations and are equipped with appropriate storage facilities (S.P. Deolalkar, 2009). However, the kiln section runs continuously when the system is active, with interruptions occurring only for maintenance

purposes, typically once or twice a year. Thus, as presented in Table 3.1, stages such as crushing limestone, milling raw materials, milling cement, and cement packaging and loading are classified as Time Bounded (TB) steps, representing controllable loads. In contrast, the clinker production stage is characterized as a continuous step, classified as an uncontrollable load (Olsen, 2012). As indicated in Table 3.1, the controllable loads make up about 60-70% of the total electrical energy consumption of cement production. Therefore, as it is highlighted in Chapter 1, these loads are appropriate for demand flexibility. To evaluate the potential for demand flexibility in the cement industry, it's essential to estimate the specific electrical energy consumption (SEC) and the daily total electrical energy consumption of the major processing steps. Additionally, determining the operating/load hours, maximum and average operation speeds, and capacity factors of the main processing stages/machines is necessary.

Thus, the parameters needed to estimate the demand flexibility potential include:

- Electricity consumption (kWh/t) of the main sub-process/machine used
- Maximum load hours of each sub-process/machine used (hr)
- Maximum production speed of each sub-process/machine (t/hr)
- Storage capacity (kt) of the semi-finished/finished products

Table 3.1: Share of EE use, operation types, and load hours/days of the main machines of cement plants (2018 Target Operating Hours in Cement Industry - Infinity for Cement Equipment, 2018) (Rombouts et al., 2021) (S.P. Deolalkar, 2009)

Main steps/machines	Share of EE[a] consumption (%)				Max. load hours and days	Continuous /TB[b]	Flexible process
	(CSI-ECRA, 2017)	(IEA, 2021c)	(Cantini, Leoni, De Carlo, et al., 2021)	Used by this study [c]			
Raw mills	25%	26%	28%	26%	20 hours/day 330 days/year	TB	Yes
Kilns	25%	28-29%	28%	27%	24 hours/day 330 days/year	Continuous	No
Cement mills	43%	31-44%	39%	40%	20 hours/day 360 days/year	TB	Yes
Fuel grinding mills	3%	3-7%	5%	3%	21 hours/day 360 days/year	TB	Yes
Crushers	2%	-		2%	12 hours/day 312 days/year	TB	Yes
Packaging & loading	2%	2%		2%	18 hours/day 360 days/year	TB	Yes

[a] EE: electrical energy, [b] Continuous: 24 hrs/day; TB: time-bounded (batch process), [c] average of the existing studies.

(a) Electricity consumption across the main stages within cement plants:

Various sources provide different breakdowns of electrical energy consumption across key processing stages in cement production. For instance, the cement grinding section accounts for approximately 43% according to (CSI-ECRA, 2017), while it is about 31-44% in (IEA, 2021c), and 39% as reported by (Cantini, Leoni, De Carlo, et al., 2021). Table 3.1 illustrates the electrical energy distribution among major sections of cement plants as outlined in these references. Thus, in this study, the average values derived from these references are used. Specific electrical energy consumption estimation relies on the average energy intensity of the case study plants (three cement plants in this case) (Mossie et al., 2023). Moreover, to estimate the total daily energy usage of each load, the production volumes of semi-finished/finished productions for the year 2020 of the case study cement plants are considered. Thus, Consequently, the electrical energy consumption of these loads/machines is estimated using data from (Mossie et al., 2023), and the figures provided by those references.

(b) Load/operating hours of the main process stages:

The main processing machines in cement plants are designed to operate for specific hours per day and days per year. The maximum operating hours of the main process steps of a cement plant were derived based on the reference books, 'Target Operating Hours in Cement Industry (2018)' (*2018 Target Operating Hours in Cement Industry - Infinity for Cement Equipment*, 2018), and 'Handbook for designing cement plants' (S.P. Deolalkar, 2009). These values are presented the table outlining the hours per day and days per year.

(c) Operating speed of the process steps:

The maximum operational speeds of the primary machines/loads within a cement plant can be estimated by taking into account their operating hours, production volume, and the average capacity factors of the cement plants being analyzed. The maximum and average operational speeds of all processes can be calculated using equation (3.7) and equation (3.8) respectively. Hence, the technical demand flexibility potential of the Ethiopian cement plants can be estimated through Equations (3.7) to (3.11) (Rombouts et al., 2021).

$$V_{max} = \frac{Q \left(\frac{Mt}{yr}\right)}{CF} / t_{oh} \left(\frac{h}{yr}\right) \tag{3.7}$$

$$V_{ave} = \frac{Q \left(\frac{Mt}{yr}\right)}{t_{oh} \left(\frac{h}{yr}\right)} \tag{3.8}$$

$$P_{L_{max}} = SEC\ \left(\frac{kWh}{t}\right) * V\ \left(\frac{(10^6 * t)}{h}\right)_{max} \frac{}{1000} \quad (3.9)$$

$$P_{L_{ave}} = SEC\ \left(\frac{kWh}{t}\right) * V\ \left(\frac{(10^6 * t)}{h}\right)_{ave} /1000 \quad (3.10)$$

where,

- V_{max}: the maximum operating speed of the machine(s), in $\frac{Mt}{h}$
- V_{ave}: the average operating speed of the machine(s), in $\frac{Mt}{h}$
- $P_{L_{max}}$: the maximum hourly loads of the machine(s), in MW
- $P_{L_{ave}}$: the average hourly loads of the machine(s), in MW
- CF: the Capacity Factor, which can be obtained by $\frac{\text{Actual production}}{\text{Installed capacity}}$
- Q_{pro}: annual production of semi-finished/finished products, in $\frac{\text{Mt}}{\text{year}}$
- t_{oh}: the maximum operating hours of the sub-processing machines/loads, in $\frac{\text{h}}{\text{year}}$, refer to Table 3.1
- SEC: the specific energy consumption of the machines, in kWh/t, obtained from the data available in the appendix, refer to Table B1.

The daily flexibility potential of the controllable process/loads of a cement plant can then be computed using equation (3.11), with the assumption that storage of semi-finished/finished products does not a limiting factor (Mossie et al., 2025).

$$E_{daily\ flexible} = \sum_{t=(24-t_{oh\,d})}^{t_{oh\,d}} (P_{L\ max} - P_{L\ \ ave}) * t\ \ + \ P_{L\ ave}\ (24 - \ t_{oh\ daily}) \quad (3.11)$$

where,

- $t_{oh\,d}$: the daily maximum operating hours of the sub-processing machines which refers to the TB machines (refer to Table 3.1).

To deliver information into the duration for which those machines/loads can be turned off without interrupting the material flows, metrics regarding material inflow and outflow along with storage capacity can be formulated. Accordingly, the minimum time required to fill up and empty the storage can be computed using the following formula (Rombouts et al., 2021).

$$t_{fill\ \&\ empty,\ sub-process} = t_{fill,\ sub-process} + t_{empty,\ sub-process} \quad (3.12)$$

$$t_{fill,\ sub-process} = \frac{S_{subprocess}}{\dot{m}_{max,\ inflow}}\ ;\ t_{empty,\ sub-process} = \frac{S_{subprocess}}{\dot{m}_{max,\ outflow}}$$

where,

- $S_{subprocess}$: the storage capacity of the sub-process
- $\dot{m}_{max,\ inflow}$: the maximum inflow of the sub-process
- $\dot{m}_{max,\ outflow}$: the maximum outflow of the sub-process

To examine the economic viability of the available DR potential for those cement plants, it is essential to assess the pricing signal of electricity in Ethiopia. Electricity tariffs should be

structured in a way that not only covers the economic costs related to power generation, transmission, and distribution but also encourage the implementation of demand-side energy management practices such as energy efficiency measures and DR strategy on the customer side (Mburamatare et al., 2022). However, the Ethiopian electric utility has a flat rate electricity tariff which is not suitable for demand response applications (*EEU Portal*, 2022). This tariff structure fails to incentivize energy efficiency measures and DR within the power sector.

As time-variant pricing is a demand-side management technique capable of stimulating DR, regulatory authorities in the electricity sector should consider implementing this pricing strategy to shape the electricity consumption pattern of their consumers. The energy mix composition of those East African countries' power grids mentioned in Chapter 1, section 1.1.2, closely resembles that of the Ethiopian power grid, with a substantial dependence on renewable energy sources including hydropower, geothermal, wind, and solar (*International Trade Administration*, 2022). Moreover, the development status and the operational cost of their power systems are more or less the same. Therefore, the average of these countries' TOU tariff prices is used in evaluating the cost-effectiveness of demand response strategy for the selected industry in this study.

3.4.2 Developing Mathematical Model to Evaluate DR Feasibility in Cement Industry

In recent times, the use of scheduling models has become increasingly common due to the prevalence of price-based tariff rates, which consider not only the quantity of electricity consumed but also the timing of its usage (B. Chen & Zhang, 2019). For industrial users, the scheduling of electricity consumption needs to align with the plant's production plan. This situation necessitates the utilization of complex mathematical scheduling models that enable integrated energy management and production planning. Hence, in this study, a mathematical modeling technique has been applied to evaluate the optimal feasibility of demand response for industrial customers. Mathematical modeling of a load management system entails non-linear relationships among multiple parameters. The scheduling of electricity consumption is determined by a decision variable that governs the operating state (working or not working) of the machine or system during a specific hour. Consequently, the proposed modeling technique for addressing the electrical energy management problem adopts Mixed Integer Nonlinear Programming (MINLP).

As illustrated in Figure 3.5, the objective of the proposed model is to reduce the hourly peak load/demand (P^p) and increase the hourly off-peak load/demand (P^o) of a typical plant. By establishing their energy consumption schedule based on the time-of-use (TOU) tariff, electricity customers can minimize their individual energy costs and holistic contribution to grid stability. To achieve this, a function is defined which incorporates the variations in TOU tariff periods (typically three-time tariff periods) and the hourly loads of the machines/equipment included in the study.

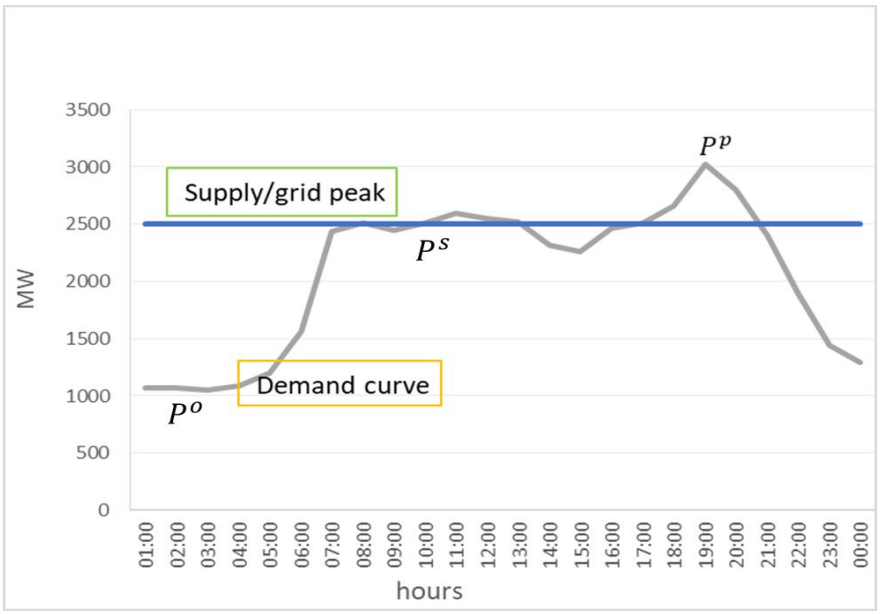

Figure 3.5: Power demand pattern for a typical day of the national power grid

The proposed model's indices, variables and parameters are outlined below as explained at (Mossie et al., 2025)

Sets/Indices:

- i: the index of the cement plant
- j: the index of the machine/equipment at the cement plant i
- t: the index of the hour of the day

Decision variable:

- $x_{i,j,t}$: binary variable showing whether the machine j works at hour t
  If the machine j of plant i is working at t, $x_{i,j,t}$ =1; otherwise $x_{i,j,t}$ =0.
  $x_{i,j,t} \in \{0\ 1\}$ – binary variables
- $p_{i,j,t}$: the electrical load of machine j of plant i during hour t (kW)

Intermediate variables:

- $P_{i,t}$: the electrical load of plant i at hour t (kW)
- P_i: the total electrical load of plant i during the day (kW)
- P_i^s: the average hourly electrical load of the plant during shoulder period (kW)

- P_i^p: the average hourly electrical load of the plant during peak period (kW)
- P_i^o: the average hourly electrical load of the plant during off-peak period (kW)

Parameters:

- $h_{i,j}$: the daily required time to operate equipment j of plant i (h).
- $\omega_{i,j}$: the hourly electrical load of the equipment j of plant i (kW).

Constants:

- d_p, d_s, d_o: the number of hours in the peak, shoulder, and off-peak periods of the day, respectively.
- e_p, e_s, e_o: hourly electricity prices (TOU tariffs) of the three time slices of the day's peak, shoulder, and off-peak periods, respectively.
- C_i: the total electricity cost of plant i during the day in the reference schedule (USD).
- J_i: the total electricity cost of plant i during the day in the optimal schedule (USD).
- l_i: the daily maximum electrical load of the cement plant i.
- $l_{i,j}$: the daily maximum electrical load of machine j of the plant i.

The intermediate variables of the model such as P_i, $P_{i,t}$, P_i^p, P_i^s and P_i^o can be obtained by the combination of the main parameters ($h_{i,j}$ and $\omega_{i,j}$), and the decision variables $p_{i,j,t}$ and $x_{i,j,t}$. As the goal of the study is to flatten the daily load curves, an objective function should be defined to reduce the hourly peak load and maximizes the hourly off-peak loads through load shifting, thereby minimizing the ratio of peak-to-off-peak demand (Manasseh et al., 2015)(Palaniyappan et al., 2024). For three- part-time slots (peak, shoulder, and off-peak periods), the objective becomes minimizing the combined peak-to-shoulder and shoulder-to-off-peak demand ratios, which is the case of this study. Thus, by applying a three-time TOU tariff structure with the peak, shoulder, and off-peak periods of the power grid, the following function is obtained (Mossie et al., 2025).

$$\text{Objective Function} = \left(\frac{P_i^p}{P_i^s} + \frac{P_i^s}{P_i^o}\right) = \frac{\left((P_i^p \times P_i^o) + (P_i^s)^2\right)}{(P_i^s . P_i^o)} \tag{3.13}$$

Hence, the objective function aims to minimize the function defined in equation (3.13), resulting in decreased demand during peak periods and increased demand during off-peak periods for the demand profile of the case study cement plants (Mossie et al., 2025) (Nguyen et al., 2012). Therefore, the objective function is:

$$\text{Min} \frac{\left((P_i^p \times P_i^o) + (P_i^s)^2\right)}{(P_i^s . P_i^o)} \tag{3.14}$$

where,

- $P_i^p = \frac{\left(P_{i,18}^p + P_{i,19}^p + P_{i,20}^p + P_{i,21}^p + P_{i,22}^p\right)}{d_p}$ (3.15)

- $P_i^o = \frac{(P_{i,23}^o + P_{i,24}^o + P_{i,1}^o + P_{i,2}^o + P_{i,3}^o + P_{i,4}^o + P_{i,5}^o + P_{i,6}^o)}{d_o}$ (3.16)
- $P_i^s = \frac{(P_{i,7}^s + P_{i,8}^s + P_{i,9}^s + P_{i,10}^s + P_{i,11}^s + P_{i,12}^s + P_{i,13}^s + P_{i,14}^s + P_{i,15}^s + P_{i,16}^s + P_{i,17}^s)}{d_s}$ (3.17)
- $P_{i,t} = \sum_j p_{i,j,t} \quad \forall\, i, t$ (3.18)
- $P_i = \sum_t P_{i,t} \quad \forall\, t$ (3.19)

Constraints: In the optimal scheduling model, the daily cost of electricity should be lower than the cost incurred by the plants during conventional scheduling. The total electrical load of each machine and each plant remains constant on a daily basis, ensuring that equations (3.20), (3.21), and (3.22) are satisfied. Here, C_i, l_i and $l_{i,j}$ are obtained by collecting data.

$$\left(\left(P^p * d_p * e_p\right) + (P^s * d_s * e_s) + (P^o * d\_o * e_o)\right) < C_i \quad (3.20)$$

$$\sum_{t=1}^{24} P_{i,t} = l_i \quad \forall\, i \quad (3.21)$$

$$\sum_{t=1}^{24} p_{i,j,t} = l_{i,j} \quad \forall\, i, j \quad (3.22)$$

Based on this model, the amount of electrical load used by machine j of plant i during time t ($p_{i,j,t}$ variable) is equal to 0 or $\omega_{i,j}$ depending on whether the machine is working or not. It is assumed that the work sequence of each plant is started after some setup time has passed at the beginning of 24-hour period (Mossie et al., 2025). However, the work sequence and setup times of each machine of the plant can be obtained as data. Such that:

$$p_{i,j,t} = x_{i,j,t} * \omega_{i,j} \quad (3.23)$$

$$\sum_{t=1}^{24} x_{i,j,t} \leq h_{i,j} \text{ for } \forall\, i, j \quad (3.24)$$

To ensure continuous running of machine j that starts at $\sigma_{i,j}$, and does not stop until the optimal total hours of $\tau_{i,j}$;

$$\text{If } x_{i,j,to} = \sigma_{i,j} = 1,\ \sum_{t=1}^{24} x_{i,j,t} = \tau_{i,j}, \text{ then } \sum_{t=\sigma_{i,j}}^{\tau_{i,j}} x_{i,j,t} = \tau_{i,j} \quad (3.25)$$

The final constraints of the model are given in equations (3.26) and (3.27).

$$p_{i,j,t} \geq 0 \quad \forall\, i, j, t \quad (3.26)$$

$$x_{i,j,t} \in \{0, 1\} \quad \forall\, i, j, t \quad (3.27)$$

During this mathematical model development, the following assumptions are taken:

- The selected plants work for 24 hours (in three 8 hours shifts).
- The plants use the specified TOU tariffs.
- The final production activities of plants are not interrupted.

- It is assumed that the storage available in each subsection has the capacity to store production, ensuring that the sub-process machines can be turned off without interrupting material flows.

Alternatively, the objective function can be defined in such a way that minimizes the total daily energy cost (J_i) of the cement plant subject to energy demand and production constraints.

$$J_i = \sum_{t=23}^{6} (e_o \times P_{i,t} \times 1h) + \sum_{t=7}^{17} (e_s \times P_{i,t} \times 1h) + \sum_{t=18}^{22} (e_p \times P_{i,t} \times 1h) \quad (3.28)$$

The constraints stated in Equations (3.21) - (3.27) should be satisfied. It is verified that both approaches yield the same results.

However, these two objective functions have different implications. The first objective function focuses on minimizing peak demand in the power grid. The insights gained can help policymakers and grid managers in designing appropriate electricity pricing rates and incentive packages for industrial customers, encouraging them to schedule their loads optimally. Currently, the Ethiopian power grid uses flat rate pricing, which does not incentivize proper load scheduling. Hence, this study applies the average TOU pricing rates of East African countries, taking their energy mix into consideration (see section 1.1.2). The second objective function, however, targets to minimize costs in the cement industry, motivating cement managers to schedule their loads efficiently. Generally, the two objective functions can address and target both stakeholders, but in this study, the analysis is based on the preference of the first objective function.

The proposed model becomes a MNLP. It is non-linear due to the ratio of variables, and a mixed-integer program due to the binary variable, which takes a value of 0 or 1, and the hourly load of the machine, which can take any non-negative real number. The model is then solved using a GRG nonlinear solver, an Excel add-in for optimization (Powell & Batt, 2008), or a Gekko solver built into Python (Beal et al., 2018) for each plant. As mentioned earlier, the daily electrical energy consumption schedule for each plant can be optimized. Subsequently, the previous power consumption pattern of each plant can be compared with the optimized schedule pattern. This system enables the derivation of the most balanced daily power consumption schedules without deviating from the existing production plans of the sampled cement plants and maintaining the total daily energy consumption of each machine and plant. As a result, the impact of grid instability originating from the cement plants is minimized, achieving the objective of the study. To enhance the effectiveness of this method, the number of users of this DSM approach should be maximized.

3.5 Investigating Techno-Economic Analysis of Waste Heat Recovery Power Plants

3.5.1 WHR Configuration in Cement Plants

In cement production, where substantial heat is released, strategies to minimize waste heat loss often involve implementation of Waste Heat Recovery (WHR) systems. These approaches are designed to capture waste heat from different stages of the production process and recover it for useful applications, such as electricity generation, preheating raw materials, or heating water. By implementing these facilities, cement plants not only improve their sustainability but also gain the ability to offset their electricity consumption through co-generation (thyssenkrupp-polysius, 2022). There are three main types of conventional WHR technologies used by cement plants for generating power from their waste heat sources differentiated by their types of working fluid (Khater et al., 2021): Steam Rankine Cycle (SRC), Organic Rankine Cycles (ORC), and Kalina Cycle (KC). In power generation, their operation is based on the Rankine cycle, a thermodynamic cycle that converts heat into work (power in this case) (IFC, 2014). The heat is supplied externally to vaporize the working fluid or water in the boiler into high-pressure steam which expands in the turbine to produce power by rotating it and through the induction generator. The expanded vapor is condensed to low-pressure liquid in the condenser and is recycled back to the boiler to continue the cycle (Hedman, 2019). Figure 3.6 demonstrates the working of the Rankine cycle and the main components of the waste heat recovery plant. In general, the power conversion efficiency of WHR technologies is in the range of 18 – 26% (IFC, 2014).

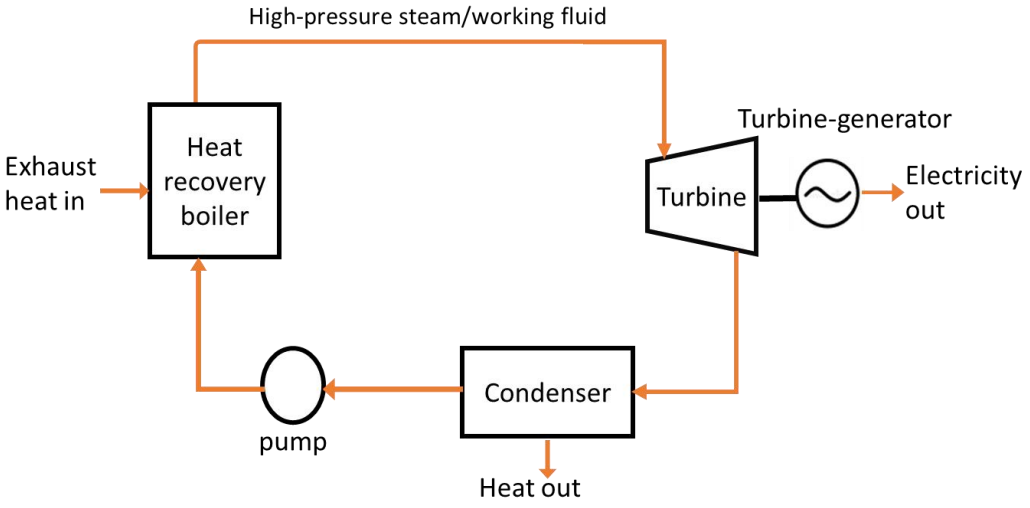

Figure 3.6: Basic Rankine cycle and main components of WHRPP, derived from (IFC, 2018)

The main features of the three WHR technologies are outlined in different literature including

(IFC, 2017d), (Confederation of Indian Industry, 2010)(Khater et al., 2021). Among the three options, the SRC is the most commonly used Rankine cycle system for waste heat recovery power generation in cement plants, utilizing water as the working fluid. Steam is generated in the waste heat boiler, which then drives a steam turbine and generator to produce electricity. Generally, SRC technology is economically preferable where the source heat temperature exceeds 260° C (Hedman, 2019). While, ORC typically uses a high molecular mass organic working fluid, such as butane or pentane, characterized by a lower boiling point, higher vapor pressure, molecular mass, and mass flow compared to water. These properties collectively contribute to higher conversion efficiencies than those achievable with a steam system. The ORC systems can be utilized for waste heat sources as low as 150° C (Confederation of Indian Industry, 2010). It is a similar thermodynamic cycle as SRC in terms of its operation, but they exhibit strong differences in terms of operating temperature range and the working fluid of the cycles. In general, it has advantages such as low maintenance requirements, high safety, and good thermal performance in recovering waste heat. KC is a modified version of the basic Rankine cycle which can utilizes a binary mixture of water and ammonia as the working fluid, offering enhanced conversion efficiency from the exhausted heat source compared to other technologies. It takes advantage of the ability of ammonia-water mixtures to effectively utilize variable and lower-temperature heat sources. With an operational temperature range spanning from 95°C to 535°C, the Kalina cycle is purportedly 10 to 20% more efficient than ORCs at similar temperature levels, and 20 to 40% more efficient than SRC (Fierro et al., 2022).

3.5.2 Power Output and Efficiency Estimation

Estimating the annual energy output from waste heat potential involves straightforward conversions and efficiency considerations that are standard in the field of energy engineering (Forman et al., 2016) (Khater et al., 2021). The electrical power output (P_{ele}) from the waste heat recovery power plant can be estimated by:

$$P_{ele} = \eta * \dot{Q}_{avaliable} \tag{3.28}$$

Where: $\dot{Q}_{avaliable}$ is the rate of heat available for recovery from the waste heat source, and can be estimated by:

$$\dot{Q}_{avaliable} = \dot{m} * c_p * (T_{inlet} - T_{outlet}) \tag{3.29}$$

Where: $\dot{m}$ is the mass flow rate of the waste heat stream, c_p is the specific heat capacity of the waste heat stream, and T_{inlet} & T_{outlet} are the inlet and outlet temperatures of the waste heat stream, respectively. However, in this study, $\dot{Q}_{avaliable}$ is estimated directly from the utilized thermal energy in the kiln section of the case study cement plant, as it is the portion of heat wasted through the preheater exhaust gas and clinker cooler hot air (refer to Figure 3.7).

As stated in Figure. 3.7, based on literature 33% of the supplied heat is lost through the pre-heater exhaust gas and clinker cooler air. However, this amount cannot be available for electricity production, as we cannot cool it all the way down to the ambient. According to (IFC, 2014), the average temperature level at the pre-heater exhaust gas is between 280°C - 450°C. The variation depends on factors such as the stage of the pre-heater, the heat recovery equipment installed, and the operation conditions. The temperature level of the air exiting the clinker cooler ranges from 250°C to 350°C and the variations could be due to factors such as type of cooler and clinker production rate.

The case study cement plant has a 6-stage pre-heater, and a grate type cooler, thus, the average temperature level of the waste heat stream (T_{inlet}) can be assumed to be 300°C, and the temperature level of the colder side (T_{outlet}) can be assumed to be 100°C. Taking these assumptions, the available energy for electricity production becomes about 67% of the 33% of the supplied heat. Based on the report by (IFC, 2014), the overall power conversion efficiency of WHRPP is in the range of 18 – 26%.

In order to evaluate the viability of a WHRPP for the case of a particular cement plant in Ethiopia, the annual average thermal energy consumption of the case study cement plant and its percentage of recoverable energy extracted from the exhausted pre-heater and clinker cooler gasses have to be first estimated. As illustrated in (Mossie et al., 2023), the annual thermal energy consumption of the case study plant in 2020 was 6.3 PJ. Since primary data for estimating the specific heat losses at the case study cement plant is unavailable in its documentation, secondary data from similar cement plants of comparable capacity has been utilized. The collective average values extracted from literature, as detailed in Chapter 2, section 2.3.1, regarding energy efficiency and its associated losses in cement production, are depicted in the Sankey diagram (refer to Figure 3.7), which has been employed to estimate the heat losses for the case study cement plant. The average thermal energy efficiency of a typical kiln is about 55%. Consequently, approximately 45% of the total thermal energy utilized in a cement plant is dissipated through various ways. Specifically, the combined average waste

heat that can be extracted from the preheater exhaust gas and the clinker cooler air amounts to about 33% of the total thermal energy utilized in a typical plant.

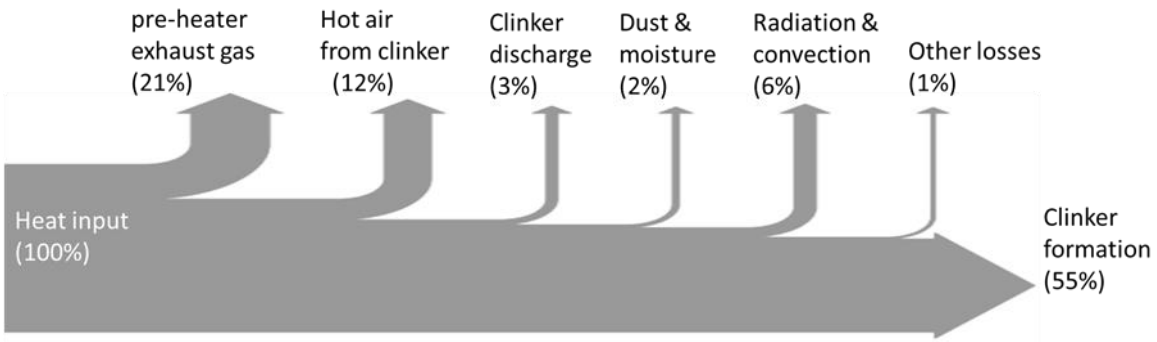

Figure 3.7: The average heat/energy balance of a typical cement plant (with approximate figure scaling)

3.5.3 Metrics Used to Evaluate WHR Economic Performance

The Levelized Cost of Energy (LCOE) is a measure of the overall life cycle cost of the power plant per unit of electrical energy generated (Haghi, 2024). It is a convenient measure of the overall competitiveness among various generation options compared in unit cost of electricity generation (Hedman, 2019). The LCOE is calculated by summing the discounted costs over the plant's lifetime, spread across the discounted units of energy produced over the same period. This approach requires future costs to be expressed in present value terms. The main factors that determine LCOE can be split into those that determine cost and those that determine energy generation. Hence, the LCOE is estimated using equation 3.32 in this study.

$$LCOE = \frac{CC+\sum_{i=1}^{y}\frac{A_y}{(1+d)^y}}{\sum_{i=1}^{y}\frac{E_y}{(1+d)^y}} \quad (3.30)$$

Where: CC is the initial capital cost (Million USD), A_y is the annual running cost (Million USD), E_y is the annual electricity generation (MWh), y is the lifetime of the plant, and d is the discount rate.

Thus, to determine the appropriate technologies for the particular cement plant, the Life Cycle Costs (LCCs) of the waste heat recovery power generation plants (WHRPGP) utilizing three WHR technologies, are first conducted. This evaluation encompasses the main expenses, such as initial capital investment cost, operation & maintenance expenses, major equipment replacement costs, revenue obtained from energy generation, and salvage value (Fierro et al., 2020) (Kazmi & Khan, 2012). In other words, these factors: capital cost required for starting

the project, operation & maintenance cost for system operation, replacement expense for major components or periodic equipment overhauls, revenue obtained from energy generation, and salvage value at the end of the life span of the system are examined to determine the feasibility of a WHHPP in particular cement plant. Hence, based on (Kazmi & Khan, 2012) (ESFC, 2021) (Fierro et al., 2020) (Fierro et al., 2022), the following definitions and equations are applied in this study.

a) **Capital (Investment) Cost (CC):** it is the upfront investment cost required to purchase and install the WHR system. It mainly includes the payment of the project for the initial year including the cost of the design of the system, initial expenses for equipment, civil works and equipment installation.

b) **Operation & Maintenance Cost (OMC):** it is the sum of the whole yearly operation and maintenance schedule cost associated with the WHR plant including inspection costs, property tax, insurance, salaries of operation staff, and cost of scheduled maintenance. The lifetime OMC is estimated by the following equation.

$$\text{TOMC} = \sum[OMC * (1 + r_M)^y] \quad (3.31)$$

Where: TOMC is the total operation and maintenance cost during its lifetime, and r_M is the annual incremental factor of operation and maintenance.

c) **Replacement Cost (RC):** it is the total cost of the major equipment repairing and replacement over the service period of the equipment and/or the system. This cost occurs periodically during major overhauls of generators, turbines, and other equipment and this periodic time can be taken once per four years.

$$TRC = \sum [RC * (1 + r_S)^Z] \quad (3.32)$$

Where: TRC stands the total spare parts cost over the lifetime of the system, r_s is the equipment replacement cost factor over a year (increasing or decreasing as per the market), and Z is the number of specific years for overhauling after every four years.

d) **Salvage value (SV):** it is the value of the system's components and materials that can be recovered through resale, recycling, or disposal at the end of its useful life. It mainly depends upon the condition and obsolescence of the system.

$$SV = \frac{CC}{(1+dr)^y} \quad (3.33)$$

Where: dr is the depreciation rate every year (usually taken as 10%)

e) **Revenue obtained from energy generated (TREG)**: the total amount of money saved by utilizing the cogenerated energy, equivalent to the value of energy saved during the lifetime of the plant, which aligns with the cost of purchasing the same quantity of energy from the power utility.

$$TREG = \sum_{i=1}^{y} [REG * (1 + r_E)^y] \quad (3.34)$$

Where: REG is the cost of energy obtained during the first year of the plant, and r_E is the energy price factor which can increase or decrease depending on the market.

Hence, the calculation of the Life Cycle Cost (LCC) for the waste heat recovery power plant can be done by including all the expenses explained above, such that:

$$LCC_y = CC + TOMC + TRC \quad (3.35)$$

There are several methods for evaluating the economic feasibility of investment projects, including waste heat recovery systems in cement plants as explained in (ESFC, 2021). In this study the Net Present Value (NPV) approach which is a commonly used technique is applied in this study with equation 3.39 (Fierro et al., 2020) (Fierro et al., 2022).

$$NPV = \sum_{i=1}^{y} \left[\frac{F_y}{(1+d)^y}\right] - CC \quad (3.36)$$

Where: y is the period (y = 25), d is the discount rate, and $_y$ is the net cash flow over the plant lifetime (y), such that:

$$F_y = LCC_y - \sum [REG * (1 + re)^y] - \frac{CC}{(1+dr)^y} \quad (3.37)$$

To calculate the LCOE, LCC, and NPV for each WHR option, it is required to define a discount rate and a lifetime period. The technical lifetime depends on the characteristics of the technologies. The discount rate is supposed to reflect the (risk) preference of the investor and the cost of capital (Hasanbeigi et al., 2011). Discount rates vary strongly among the different studies assessing the costs and potentials of energy conservation investments. It ranges from low discount rates of 8% to high discount rates up to 30% rates (Fleiter et al., 2009). For this analysis, a 30% nominal discount rate is used, reflecting various risks associated with the project, including political and economic instability, financing challenges, and the existing inflation rates in Ethiopia (Tesema & Worrell, 2015) (Mossie et al., 2023). As explained in (Martin, 2016), the effect of inflation on costs and benefits can be included into the model.

Sensitivity analysis allows for variations in this rate to evaluate its impact on the results. Thus, using the NPV, an investment should be feasible only if NPV>0, while in the case of alternative investments that are compared, the best of them would be the one with the higher NPV (ESFC, 2021).

3.5.4 Estimating Emission Mitigation Potential of the WHR Power Plants

Onsite waste heat recovery (WHR) power plants in the cement industry can provide up to 30% of the electricity demand for cement production (Marenco-Porto et al., 2023), reducing dependency on the national power grid and onsite diesel plants. In addition to partially replacing the on-grid electricity for cement production, the implementation of WHRPPs allows for the reduction of the CO_2 emissions associated with cement production (Jaiboon et al., 2021). The emission reduction potential of the WHR power plants for the case study cement plant can be estimated by the following equation.

$$ER_{co_2} = EG_{WHR} * EF_{ele} \quad (3.38)$$

Where: ER_{co_2} is the annual total CO_2 emission reduction potential, in tons per year, by the WHR power generation, EG_{WHR} is the annual electrical energy generated by the waste heat recovery power plant, and EF_{ele}, in $kg\ CO_2\ /kWh$, is the electricity grid GHG emission factor. The emission factor for the Ethiopian power grid is estimated according to the UNFCCC methodological tool (United Nations, 2017). Thus, WHR power plants can improve the overall energy efficiency of cement plants by capturing and utilizing waste heat that would otherwise be released into the atmosphere. This system can also reduce emissions, lower energy bills, and improve the competitiveness and sustainability of cement production in general (Exergy, 2024).

3.6 Industry Survey, Data Collection, and Analysis

As part of this study, a thorough industry survey was conducted among the main cement producer plants in Ethiopia to collect research input. Seven cement plants have been selected based on their production capacity and ease of access for on-site visits and data collection.
These plants collectively represent approximately 85% of the country's production share as of 2020. Among the surveyed cement plants, five are the largest producers in the country, while the remaining two are medium-sized cement plants. (IFC, 2017). Necessary data has been collected and analyzed from which the electrical energy, thermal energy and CO_2 emission intensities of the surveyed cement plants are obtained. The different types of technologies used, process types, and measures applied have also been assessed (refer to Table 3.2). Thus,

a detailed data collection form has been developed, and used to obtain information about the selected cement plants. The data, which are required as input variables for this study, are primarily collected from the main cement processing stages which includes the amount of raw materials used in tonnes per year, the amount of additives that are dried and ground (tonnes per year), the annual production of clinker (tonnes per year) from each kiln, cement production (tonnes per year) by type and grade (see Appendix A).

Table 3.2: Emission factors, conversion factors, and other assumptions (IPCC, 2006)(United Nations Framework Convention on Climate Change [UNFCCC], 2013)

EF[a] for Coal combustion ($kgCO_2/GJ$)	EF for electricity grid ($kgCO_2/kWh$)	CF[b] for EE[c] into PE[d]	Calorific value of coal (Kcal/kg)	Unit price of coal (USD/GJ)	Unit price of EE (USD/MWh)	EF_{clc} (Mt CO_2/Mt clinker)
94.6	0.006	1.37	5000	10.1	64.4	0.52

[a] EF: Emission Factor, [b] CF: Conversion Factor, [c] EE: Electrical Energy, [d] PE: Primary Energy

Moreover, the input data process encompasses various elements, such as annual energy usage for clinker and cement production, annual costs of electrical energy, fuel & materials utilized, technologies employed, clinker & cement-making capacities, as well as age of the plants. Initially, the collected data are analyzed according to comparison and benchmarking standards. To convert electrical energy (EE) into primary energy (PE), a conversion factor of 1.37 is applied, accounting for transmission and distribution losses of the grid (19%) and power plant efficiency (10%) (The World Bank, 2018). Additionally, the conversion factor used for calculating CO_2 emissions from energy consumption, as shown in Table 3.2, is derived from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The emission factor for the Ethiopian power grid is estimated according to the UNFCCC methodological tool and assumed to be 0.006 kg CO_2/kWh. The unit price of electricity (USD/kWh) is sourced from Ethiopian Electric Utility for high-voltage customers. The average unit price for fuel is determined by considering the unit price of foreign coal and local coal consumption in 2020 for each surveyed plant. During the study year, the quantities of heavy fuel oil (HFO), pet coke, diesel, and alternative fuel used by the surveyed cement plants were negligible, and they are thus not included in the study. To convert coal consumption (in tonne) into calorific value (in kcal), a conversion factor of 5000 kcal/tonne of coal is used, representing the average calorific value of one ton of coal used by the surveyed cement plants in 2020 (United Nations Framework Convention on Climate Change [UNFCCC], 2013). Costs are denoted in US dollars, with an average

exchange rate applicable for the year 2020. The summary of collected data from the surveyed cement plants is put in Appendix A.

Table 3.3: Summary information on production capacity and technology used by the Ethiopian cement plants (survey results)

Plants	Production lines	Production started	Production capacity		Raw material grinding mill type	Cement grinding mill type	Coal grinding Mill type	Kiln technology
			Clinker capacity (ton/day)	Cement capacity (Mt/year)				
Plant 1	Line 1	2015	5000	2.5	Vertical Roller Mill	Vertical Roller Mill	Vertical Roller Mill	6 stage pre-heater, pre-calciner & grate cooler
Plant 2	Line 1	2012	5600	2.3	Vertical Roller Mill	Ball Mill	Ball Mill	5 stage pre-heater, pre-calciner & grate cooler
Plant 3	Line 1	1984	1000	2.2	Ball Mill	Ball Mill	Ball Mill	Vertical shaft kiln
	Line 2	1990	2000		Ball Mill	Ball Mill	Ball Mill	5 stage pre-heater
	Line 3	2012	3000		Vertical Roller Mill	Ball Mill	Ball Mill	6 stage pre-heater, pre-calciner kiln
Plant 4	Line 1	2005	960	1.2	Ball Mill	Ball Mill	Ball Mill	5 stage pre-heater rotary kiln
	Line 2	2014	2880		Vertical Roller Mill	Ball Mill	Ball Mill	5 stage pre-heater rotary kiln
Plant 5	Line 1	2016	3000	1.4	Vertical Roller Mill	Ball Mill	Ball Mill	5 stage pre-heater, pre-calciner & grate cooler
Plant 6	Line 1	2005	1479	0.77	Ball Mill	Ball Mill	Ball Mill	5 stage pre-heater, pre-calciner & grate cooler
Plant 7	Line 1	2014	670	0.7	Ball Mill	Ball Mill	Ball Mill	Vertical kiln
	Line 2	2014	670		Ball Mill	Ball Mill	Ball Mill	Vertical kiln

Table 3.3 provides a summary of the production capacities of the surveyed Ethiopian cement plants. These plants use the dry-process cement production method, in which the raw materials are dried and blended before entering the kiln. Compared to the wet-process production method, this type of process requires higher electrical energy and less thermal energy to produce a tonne of cement. In the wet process, raw materials are mixed with water to form a slurry prior to entering the kiln. Coal serves as the primary thermal energy source, while the national electric grid supplies electrical energy for their production. According to the Ethiopian Ministry of Trade and Industry, energy costs in the Ethiopian cement industry constitute approximately 50-60% of the total annual production cost, exceeding the global average of 30-40% (GoE, 2013). Most plants employ multi-stage New Suspension Pre-heater (NSP) rotary kiln technology (Tesema & Worrell, 2015) known for its energy efficiency compared to the older vertical shaft kiln (VSK) technology (Boateng, 2016). Plant 1, stated in Table 3.3, utilizes vertical roller milling (VRM) technology for both raw material and final cement grinding, while other cement industries typically utilize a combination of VRM and ball mills for raw material and final cement grinding, respectively (GoE, 2013).

As previously mentioned, the cost of energy in these cement plants constitute a substantial portion of the total production cost. The surveyed plants employ various kiln technologies at their pyro-processing stage and different types of mills for raw material preparation and cement grinding stages. Therefore, evaluating these plants' current specific energy consumption and CO_2 emissions is vital. Energy savings and the subsequent reduction of associated CO_2 emissions can be accomplished by implementing potential energy efficiency measures.

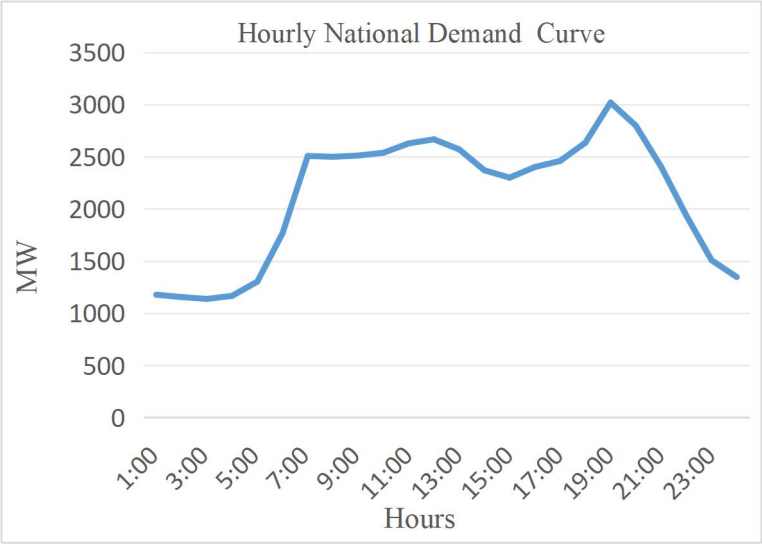

Figure 3.8: Hourly demand curve of the Ethiopian power grid (the average of December 2020)

The hourly demand curve of the Ethiopian power system, based on 2022 data from the National Load Dispatch Center, is depicted in Figure 3.8. The period from October to May is generally the dry season for Ethiopia (Jenna Jolie, 2024). As electricity is dominantly dependent on hydro, the month of December is selected to see the hourly demand fluctuation during the critical season. As shown in the Figure, there are high electricity demand fluctuations in the grid, highlighting three distinct periods: peak (18:00 – 22:00), shoulder (7:00 -17:00), and off-peak (23:00 – 6:00). These periods have been utilized to develop optimal energy management strategies incorporating demand response techniques in this study. They are crucial for grid operators to effectively manage demand and supply throughout the day. During peak periods, matching supply and demand poses significant challenges for the grid, often resulting in system instability, power fluctuations, and outages, which can jeopardize system reliability (Heilmann et al., 2021). The use of supplemental generation during peak times can make up supply deficits, but this approach is typically not economical as stated in Chapter 1. Therefore, the application of DR in this system can help

solve these challenges, reduce energy costs for users, and facilitate the integration of high levels of intermittent renewable energy sources into the system (refer to Chapter 2).

To investigate the techno-economic performances of waste heat recovery power plant, the necessary parameters are summarized in Table 3.4. As outlined in section 3.5, the energy conversion efficiency of waste heat recovery power plants varies in the range of 18 -26%, depending on the types of technologies employed (IFC, 2014). Again, according to (Jouhara et al., 2018) and (IFC, 2014), Kalina cycle offers a 20% to 40% performance improvement relative to conventional waste heat systems. While ORC is 15 -20% more efficient than steam cycle plant. Hence, energy conversion efficiencies of 20%, 24%, and 26% are applied in this study for steam RC-based WHRPP, ORC-based WHRPP, and Kalina RC-based WHRPP, respectively. Based on (Köse et al., 2022), the annual operating hours of a typical WHRPP can reach to 8000 hours, and (Confederation of Indian Industry, 2010), recommends that high operating hours of WHRPP are better for project economics. According to (Climatescope, 2023), the average unit price of electricity in Ethiopia in 2020 was 0.05 USD per kWh. The life span of the plant is assumed to be 25 years. Thus, the detailed information is presented in Table 3.4.

Table 3.4: Summary of parameters for each type of WHRP for the case study cement plant

Items*	SRC- based WHRPP	ORC- based WHRPP	Kalina RC-based WHRPP
Total heat (thermal) energy utilized (PJ)[a]	6.33	6.33	6.33
percentage of heat wasted through PH and clinker cooler gases[b]	33%	33%	33%
heat input at PH & AQC boilers (PJ)	1.4	1.4	1.4
heat input at PH & AQC boilers (MWh)	388.8	388.8	388.8
available thermal power (MW)	44.4	44.4	44.4
conversion efficiency (Ƞ)	20%	24%	26%
expected power generated capacity (MW)	8.9	10.7	11.5
annual operating hours (hrs)	8000	8000	8000
annual average generated energy (MWh)	71,011	71,011	71,011
lifetime (years)	25	25	25
investment/capital cost (CC), USD/kW[d]	1100	1400	1500
operation & maintenance cost (OMC)	2% of CC	2% of CC	2% of CC
annual increase of OMC (r_m), %	10	10	10
replacement cost (RC)	4% of CC	4% of CC	4% of CC
annual increase of RC (r_r), %	20	20	20
annual increase of energy price (r_e), %	5	5	5
annual depreciation rate (d_r), %	10	10	10
discount rate (d), %	30	30	30

*Acronyms: Ph, Pre-heater; AQC, air quenching cooler

[a] as per the plant's information (field visit), also refer to (Mossie et al., 2023).
[b] refers to Table 1 (average value)
[c] the temperature levels of the waste heat stream (T_{inlet}) and the temperature level of the colder side (T_{outlet}) are assumed to be 300°C and 100°C respectively (IFC, 2014), 67% of the heat available in the waste stream is considered for electricity generation.
[d] based on sources: (Heidelberg Material, 2021) (H. Chen et al., 2022) (Raab et al., 2021) (Tartière & Astolfi, 2017) (Fierro et al., 2022).

The initial investment cost, and the operation & maintenance costs of the WHR power plants vary depending on different factors such as the type of WHR technology, the size of the plant, the temperature grade of the waste heat. Suez Cement Group of Companies (SCGC) in Egypt, a subsidiary of Heidelberg Cement, invested around 20 million USD to build in its Helwan factory a system to collect waste heat generated in its kiln and convert it into electrical energy. The plant has the potential to generate up to 18 MW of power for captive consumption, with 1111 USD/kW (Heidelberg Materials, 2021). While in (H. Chen et al., 2022), for 8.45 MW, the total investment cost of a conventional WHRPP was estimated to be 1080 USD per kW. According to (Raab et al., 2021) and (Tartière & Astolfi, 2017), the specific investment cost of ORC- waste heat recovery power plant is in the range of 1410-1580 USD per kW. While, The cost of implementing a KRC is usually higher than that of an ORC (Fierro et al., 2022). annual O&M costs were assumed at 2% of the investment cost for systems of systems above 5 MW for conventional WHRPPs (Hedman, 2019). While, the ORC technology has minimum O&M requirements, considered about 1% in (Köse et al., 2022). The expense for working fluid (fuel) is estimated at 1% of the capital cost for steam-based plants, 5% for ORC-based plants, and 3% for Kalina RC-based plants. Replacement costs for major equipment constitute 4% of the overall plant cost across all technology types. Moreover, according to (IFC, 2014), operation and maintenance costs (OMC) represent around 2% of the capital cost for the steam cycle plants and half of that for ORC. Due to the complexity of the technology, KRC has superior operation and maintenance costs than others. Thus, these parameters crucial for determining LCC, LCOE and NPV, are also summarized in Table 3.4.

Chapter 4: Results

In this chapter, the results of the study have been presented in four main sections. Section 4.1 illustrates the assessments of the energy and environmental performance of the Ethiopian cement industry, focusing on energy utilization and emission status, and comparing them to best practices. Section 4.2 demonstrates primarily on the investigation of energy efficiency enhancing potential in cement production. In section 4.3, the available energy demand flexibility potential of the Ethiopian cement industry and the findings of the case study cement plants with the proposed demand response model for optimizing operation and scheduling, have been presented. Finally, the techno-economic evaluations of WHRPP in the context of the Ethiopian cement plant are presented in section 4.4.

4.1 Energy and Environmental Performance Assessments of the Ethiopian Cement Industry

4.1.1 Energy Utilization and Emission Status Assessment

In this section, a comprehensive assessment of the Ethiopian cement industries is conducted, utilizing data from the 2020 production year and covering seven cement plants. Table 4.1, Figure 4.1, and Figure 4.2 present the assessment of various metrics including the energy and CO_2 intensities, clinker-cement ratio, and utilization capacity of the cement plants. The calculations of these performance indicators consider the annual cement production, annual electrical energy, and fuel consumption data from each of the plants in 2020. Energy intensities reflect the amount of energy consumed to produce one tonne of cement by each of the surveyed cement plants. Figure 4.1 highlights that Plant 3 has the highest specific electrical energy consumption to yield a tonne of cement (171 kWh/tonne), while Plant 1 demonstrates the lowest value (111 kWh/tonne). On average these plants exhibit an annual electrical energy intensity of approximately 132 kWh/tonne of cement production in 2020. Moreover, emphasizing the significance of the clinker manufacturing phase as the most energy-intensive phase in cement production, the average clinker-cement production ratio among the surveyed plants is about 80%. Additionally, the percentage utilization capacity reveals that all selected cement plants operated below their production capacity in 2020. This underutilization, which leads to energy inefficiency and material waste, is attributed to factors such as power fluctuations, market constraints, and security concerns in the country.

Table 4.1: Energy & CO_2 emission intensities, clinker-cement ratio and utilization capacity of the Ethiopian cement plants

Plants	Electrical Energy intensity (kWh/t cement)	Fuel intensity (GJ/ton cement)	Final energy intensity (GJ/ton cement)	Primary energy intensity (GJ/ton cement)	CO_2 emission intensity [a] (kg CO_2/t cement)	Clinker-cement ratio	Utilization capacity (%)
Plant 1	111	3.03	3.43	3.58	287.30	0.76	86%
Plant 2	121	3.13	3.57	3.73	296.82	0.84	88%
Plant 3	171	3.30	3.92	4.14	313.21	0.75	36%
Plant 4	130	3.23	3.70	3.87	306.34	0.89	76%
Plant 5	166	3.63	4.23	4.45	344.39	0.79	29%
Plant 6	114	3.70	4.11	4.26	350.70	0.73	44%
Plant 7	112	4.83	5.23	5.38	457.59	0.81	15%

[a] the CO_2 emission intensity used is the intensity due to fuel combustion.

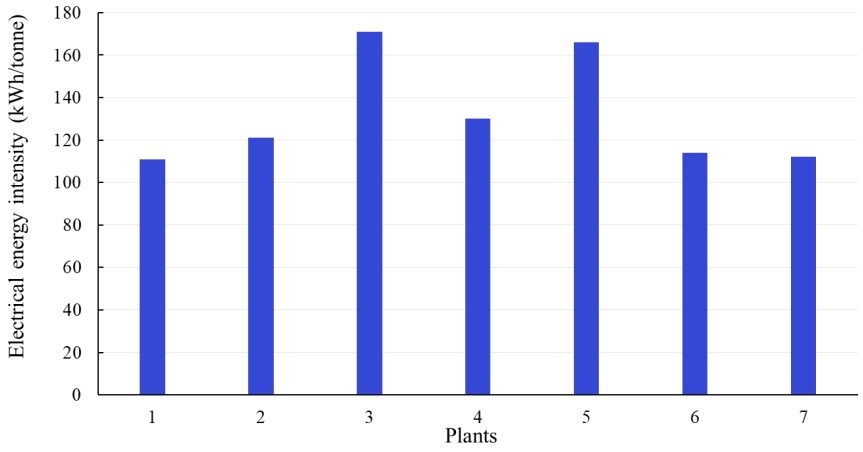

Figure 4.1: Electrical energy intensity of the surveyed cement plants in 2020

As presented in Appendix A (Table A3), the total CO_2 emissions of the seven cement plants examined in 2020 amounted to around 4.86 Mt. These emissions encompass emissions due to the calcination process, fuel combustion, and electricity consumption. Specifically, emissions attributable to calcination process accounted for about 2.82 Mt, emissions from fuel combustion were around 2.04 Mt, and emissions linked to electricity usage were about 0.01 Mt. The minimal impact of electricity usage on emissions is attributed to the predominance of renewable energy sources in the Ethiopian electricity grid. While emissions from calcination are unavoidable (~57.9%) by energy efficiency measures, those from fuel combustion (~41.9%) and electricity (~0.2%) could potentially be mitigated through the implementation of energy efficiency measures in cement plants. Consequently, the focus of the CO_2 emission reduction efforts conducted in this study lies in reducing emissions from fuel combustion.

As presented in Figure 4.2, the fuel intensities across the plants range from 3.03 to 4.83 GJ/ tonne of cement; with the highest value observed at plant 7 (4.83 GJ/tonne of cement) and the lowest at plant 1 (3.03 GJ/tonne of cement). The average fuel intensity among the seven cement plants is 3.55 GJ/ tonne of cement. Similarly, The CO_2 emission intensity resulting from fuel combustion varies from of 287 to 458 kg CO_2/tonne of cement. Although Plant 1 and Plant 2 have the lowest CO_2 emission intensities, they are the highest CO_2 emitters of all plants due to their largest share of cement production.

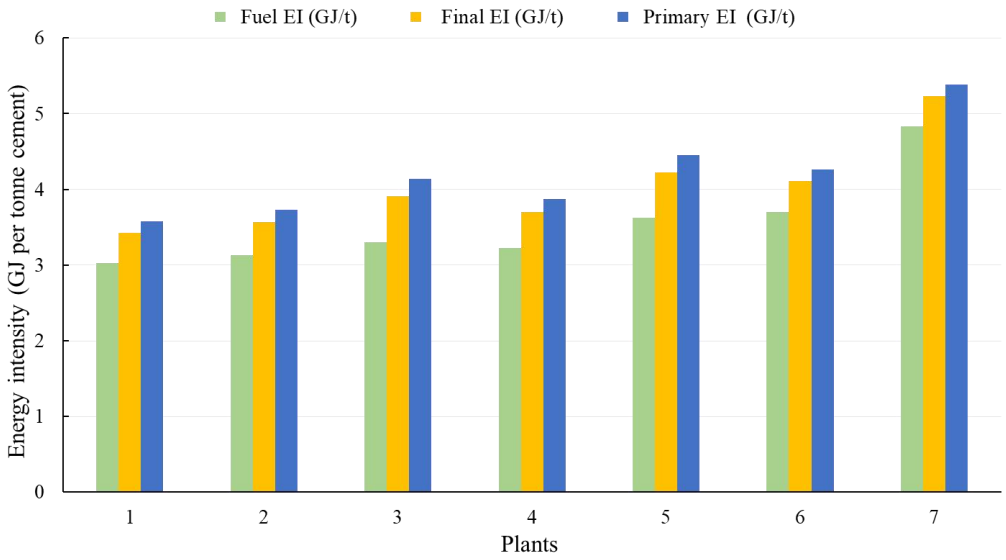

Figure 4.2: Fuel, final energy, and primary energy intensities (EI) of the surveyed plants in 2020

The findings presented so far reveal that for a unit of cement production, the surveyed cement plants exhibit varying energy consumptions and associated CO_2 emissions. The variation could stem from the differences in energy efficiency measures and technologies applied, types of cement production, capacity utilization, clinker-to-cement ratio, and specific operating procedures adopted by each cement plant. For instance, Plant 1, plant 2 and Plant 5 have single production lines equipped with at least one vertical roller grinding mill, a type of mill known to be more energy efficient (Genç, 2016), as well as 6 or 5-stage pre-heater and pre-calciner rotary kiln technology with production capacities exceeding 3000 tonnes of clinker per day (refer Chapter 3, Table 3.3). In contrast, other plants are outfitted with a ball mill, and/or a vertical shaft kiln (VSK), which is an obsolete kiln technology associated with high energy consumption and operating costs (Boateng, 2016). Some of the plants incorporate the modern New Suspension Pre-heater and pre-calciner (NSP) kiln with a special arrangement aimed at enhancing energy efficiency. Therefore, the specific energy consumption and

associated CO_2 emission intensities of these plants can be improved through the adoption of appropriate energy efficiency measures and technologies.

4.1.2 Benchmarking Assessment against International Best Practices

Figure 4.3 shows the outcomes of the analysis conducted using the BEST-Cement tool, which evaluates the energy performance of the examined cement plants against international best practices, by utilizing the energy intensity index (EII) equation mentioned in Chapter 3, section 3.2.2. This analysis has been conducted for each cement plant, and is summarized in Figure 4.3. The benchmarking is conducted based on the primary energy consumption data from the year 2020. It can be observed that all the surveyed cement plants exhibit lower efficiency levels compared to the best practice standards. The EII values of the surveyed plants range from a low of 132, indicating that the EII of the best practice is 24% below Plant 2 to a high of 192, indicating that the EII of the best practice is 48% below Plant 7. This comparison suggests that implementing feasible energy efficiency measures or technologies could potentially save 24% to 48% of the energy consumption in these surveyed plants. Thus, based on international best practices, the average primary energy saving potential across the surveyed cement plants is estimated to be around 36%.

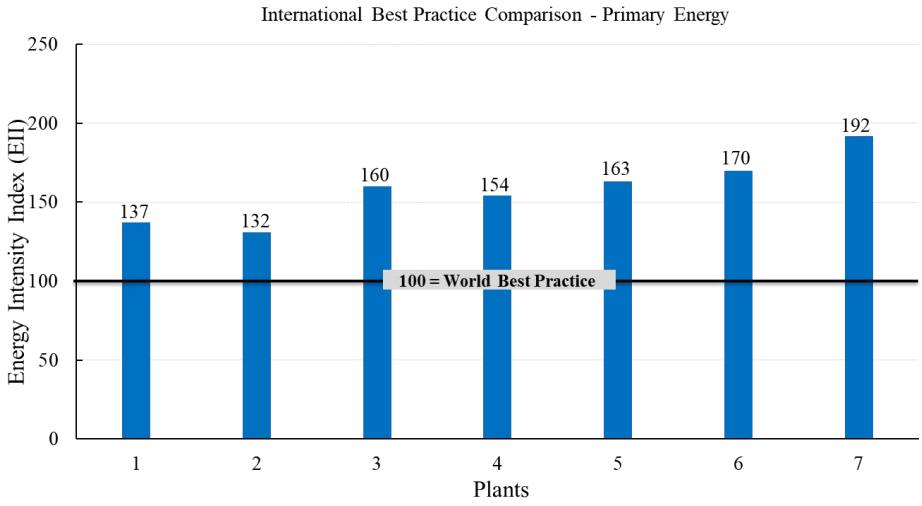

Figure 4.3: Benchmark values of the seven cement plants compared with international best practice (based on primary energy consumption)

The results of the tool indicate that the closer the EII value is to the standard value of the BEST tool (100), the more likely it is that the surveyed cement plant has implemented energy-efficient technologies and management measures. In this regard, Plant 1 and Plant 2, with EII values of 137 and 132 respectively, are in relatively good condition compared to the other

plants, despite still being far from the best practice benchmark. This evaluation aligns with some of the data collected and summarized in Table 3.3 during the industry survey.

4.1.3 Comparison Analysis of Cement Industries in Ethiopia and Sweden

In addition to the BEST-cement tool comparison assessment, the energy and environmental performance of the Ethiopian cement sector was compared against its Swedish counterpart (refer to Chapter 3, section 3.2.1). Five of the largest cement plants in Ethiopia, which have high production capacities similar to those in Sweden, were chosen for this section. To achieve this, a comprehensive review of the literature was conducted, along with interviews with experts and data gathering through site visits, discussions, and consultations with industry professionals and researchers in both countries.

Since the Ethiopian cement industry is highly dependent on imported fossil fuels including HFO, coal, and pet coke, the energy cost accounts for the major portion of the overall operational expense. To mitigate the high energy cost characteristics and corresponding CO_2 intensity, a two-step energy efficiency (EE) program, namely Thermal-Fuel-Switch, has been launched, with the assistance of the Chemical and Construction Inputs Industry Development Institute (CCIIDI) as reported by the International Cement review in 2018. CCIIDI is a responsible government stakeholder that assists in the sustainable development of the sector. In the first step of the EE program, thermal fuel is switched from HFO to coal, since coal is slightly less emission-intensive than HFO. Nevertheless, significant change in emissions was not reported after the switch. Energy cost, which accounted for 50-60% before the switch, was reduced to 40-45%. This energy cost, however, is still not within the acceptable global standard (20 - 40%) as stated by (Mossie et al., 2021).

Alternative fuel has already been introduced in the sector during the implementation phase of the second EE program (Wakeford et al., 2017). It was planned to substitute 40% of the thermal fuel with biomass (or AF) by 2020. For instance, agricultural residue (sesame and rice husks) was attempted by two of the LCP plants. One of the recently emerged LCP plants, Plant 1, reported to the CCIIDI that the successful co-processing of scrap tires and polypropylene bags was conducted in 2018 (Mossie et al., 2021). As reported by CCIIDI, Plant 1 has also begun a discussion with it to utilize 600,000 tons of banned local transformers PCB (Polychlorinated biphenyls) as a thermal carrier. Nevertheless, the share of AF is insignificant in the sector (see Figure 4.4). According to Mossie et al., 2021, the use of AF sources (such as scraped tire, municipal solid waste, agricultural residue/biomass and

other industrial wastes) in the Ethiopian cement industry is at the infant stage. The study (IFC, 2017c) indicated that refuse-derived fuel, scraped tires and biomass represent 35 million GJ/year of thermal energy in the country. In another study (Seboka et al., 2009) the potential of agricultural residues (like Coffee husk, Sesame husk, Cotton stalks, and Saw dust) and MSW as thermal carriers is estimated to be 3.6Mt of clinker/5.4Mt of cement per year. In terms of electrical energy, all the cement plants are dependent on the national electricity grid (mainly, hydropower generated), which is under immense stress due to inefficient power grid infrastructures and supply shortages as stated in (Pappis et al., 2021). It shows that frequent power interruption is hampering the sector's productivity seriously.

4.1.3.1 Energy Performance at Sweden Cement Industry

The Swedish cement industry, Heidelberg Material, the sole cement producer in the country, produced 2.7 million tons of cement in 2020 with 2.5 Mt from the Slite plant and 0.2 Mt from the Skövd plant. The plant located at Slite is the largest plant which has two modern rotary kilns with a total of 300 t/h production capacity (Heidelberg Material, 2021). The cement production is mainly driven by fossil fuels (like coal and pet coke), alternative fuels, and electrical energy (Mossie et al., 2021). At the Slite plant, the thermal energy intensity was 3.7 GJ/t clinker, while at the Skövde plant, it was 4.0 GJ/t clinker in the 2013 production year (Klugman et al., 2019). Through the adoption of EEMs, the average thermal energy intensity improved to 3.6 GJ/t clinker in 2020. The electrical energy intensity was 130.6 kWh/t cement in the same year (Mossie et al., 2021). At Heidelberg Material, "AF" denotes biomass and various forms of waste including discarded car tires, municipal solid waste, meat production residues, woody biomass, sewage sludge, textiles, paper residues, and agricultural residues. As illustrated in Figure 4.4, the utilization of AF dominated the fuel mix, reaching a 62% share in 2020. Compared to global practices, the Swedish cement industry exhibits relatively good performance in AF utilization (Mossie et al., 2021). The use of AF contributed to a decrease in fuel-related greenhouse gas (GHG) emissions in the Swedish cement sector. Moreover, energy efficiency improvements and increased adoption of AF significantly reduced the CO_2 intensity of the sector from 0.722 to 0.701 tCO2/t cement between 2010 and 2016 (Klugman et al., 2019).

In the Swedish cement industry, there exists a roadmap aimed at achieving fossil free cement production. The main levers for the roadmap includes energy efficiency enhancement, fuel switch, cement composition (blended cement and/or clinker substitutes), CO_2 uptake by concrete, and implementation of Carbon Capture and Storage (CCS) technology (refer to

Chapter 3, Figure 3.2). CCS technology is anticipated to deliver the most significant reduction in CO_2 emissions. Currently, investigations are underway at Slite on Gotland to potentially capture just over 1.8 million tons of CO_2 annually, with plans for commissioning by 2030 (Aktuell Hällbarhet, 2021). However, implementation CCS technology in industrial scale increases the power consumption of cement manufacturing (CEMBUREAU, 2022). Next to CCS, the use of biofuel (AF), changes in cement composition, and concrete CO_2 capture moderately contributes to zero CO_2 ambition. As the Energy Efficiency Improvement (EEI) iterative has already been extensively pursued in Swedish Cement production, it has a slight contribution in the roadmap. Moreover, the CemZero project, which aims to transition clinker production to electric heating, is currently in progress.

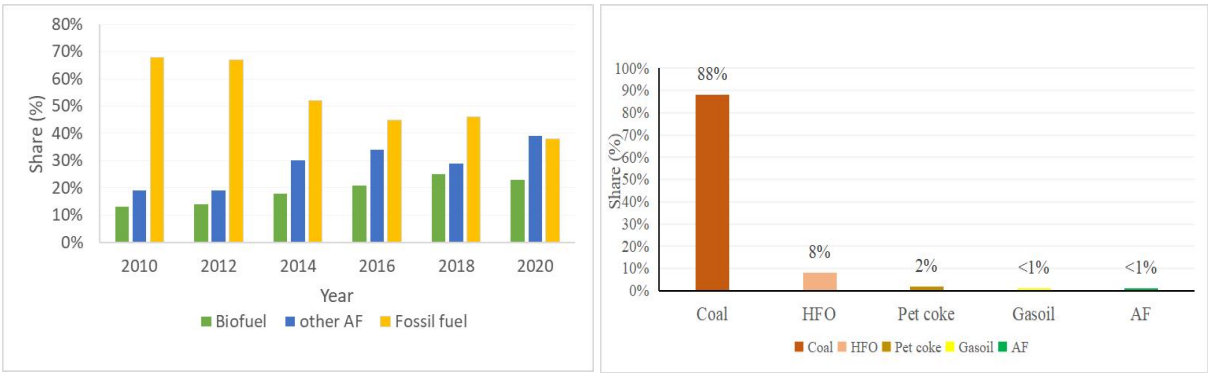

Figure 4.4: Share of thermal fuel sources in Sweden (left), and in Ethiopia (right)

4.1.3.2 Comparison between the Ethiopian and Swedish Cement Industry

Table 4.2 presents summary of the key performance parameters applied in this study. Ethiopian cement plants are more energy intensive compared to Swedish cement plant. The average thermal energy intensity of Ethiopian cement plants was 3.9 GJ/t clinker in 2020 while the Sweden cement plants' thermal energy intensity was 3.6 GJ/t clinker in 2020. Similarly, the average electrical intensity of Ethiopian cement plants was 139.8 kwh/t cement in 2020 while the Sweden cement plants consumed 130.6 kWh/t of cement. In addition to this, the average CO_2 emission level in Ethiopian cement plants was about 0.9 t CO2/t clinker in 2020, whereas the Swedish cement plant reported 0.7t CO2/t clinker in 2020. In Ethiopian cement plants, the average clinker substitute rate is about 20%. In this regard, Sweden's cement plant has a lower substitution rate (about 14%). The higher clinker substitution rate in Ethiopian cement plants comes from the use of large fraction of Pozzolanic materials (such as Pumice/Sandstone/Sand) in the production of PPC. On the other hand, Sweden's cement plant uses less fraction of clinker substituting materials such as blast furnace slag (from steel

production) or fly ash (from Coal processing) to produce slag/fly ash-based Portland cement. Replacing the amount of clinker or limestone with calcined lime and/or clinker substituting materials reduces CO_2 emission intensity.

Table 4.2: Key comparison parameters (for Ethiopian and Swedish cement industry)

No.	Parameters	Ethiopian Cement Industry	Swedish Cement Industry
1.	Percentage of alternative fuel/energy used in 2020	less than 1%	62%
2.	Annual average thermal energy intensity (GJ/t clinker)	3.9	3.6
3.	Annual average electrical energy intensity (kWh/t cement)	139.8	130.6
4.	Average emission intensity (tCO_2/t clinker)	0.9	0.7
5.	Clinker-to-cement ratio	80%	86%

Thus, Sweden cement plant has better energy and environmental performances as compared to the Ethiopian cement plants. This is due the fact that, the Sweden cement plant has already implemented most of the cement specific energy efficiency measures/technologies, including the Waste Heat Recovery Power Plant (WHRPP) that produce heat and also electricity with a generating capacity of 8.8 MW, large use of alternative fuels that reached 62% of fuel share in 2020. However, these measures and practices require a detailed study in the context of the Ethiopian cement industry.

In the cement industry, emissions are categorized into two types: process emissions, which account for over 50% of total emissions, and energy use emissions, which make up the remaining portion. This study focuses on comparing energy related emissions. Additionally, a portion of emissions arises from electricity use, where the Ethiopian electricity utility has a lower emission factor compared to the Swedish electricity grid, despite both grids being primarily dominated by renewable energy sources: over 90% for Ethiopia and about 67% for Sweden. These factors contribute to the estimated variations in emission intensity between the two countries. However, the variation remains significant as it reflects the specific emissions per ton of production in 2020.

4.2 Investigation of Energy Efficiency-Enhancing Potential in Cement Production

4.2.1 Evaluations of Potential Energy Efficiency Measures for Cement Plants

In this section, the focus is to demonstrate the potential for improving energy efficiency within the Ethiopian cement industry using the methodology outlined in Chapter 3. Through the application of a bottom-up energy conservation supply curve model, the feasibility of implementing various energy efficiency measures and technologies (EEMs) is examined in terms of both technical viability and cost-effectiveness. The selected energy efficiency measures and technologies are detailed in Table 4.3, along with their specific energy savings, potential reductions in CO_2 emissions, and associated capital costs. These measures represent established technology options available in both the Industrial Energy Efficiency Technologies Database, and in the BEST-Cement tool, offering significant opportunities for decreasing energy consumption and CO_2 emissions within the cement industry. Although approximately fifty energy efficiency measures and technologies are cataloged in the reference documents, this study focuses on twenty-eight of them. Our industry survey indicates that many Ethiopian cement plants have not yet fully adopted these measures. The specific CO_2 emission reduction potential of each measure is calculated based on the reduction in energy usage. Some measures exhibit negative values for electrical energy savings, indicating that while they offer fuel-saving benefits, they require additional electrical energy. Nonetheless, the overall primary energy savings resulting from these measures remain positive.

Then, utilizing the data provided in Table 4.3 and following the methodologies outlined in Chapter 3, separate electrical energy conservation supply curves (EECSC) and fuel conservation supply curves (FCSC) are developed to evaluate the cost-effective and technical potentials of the selected measures within the surveyed cement plants. Among the twenty-eight energy efficiency measures summarized in Table 4.3, seventeen belong to electrical energy efficiency and are incorporated into the EECSC, while eleven focus on fuel efficiency and are integrated into the FCSC. Moreover, the CO_2 emission reduction potential of these measures is also evaluated on these cement plants.

Table 4.3: Selected energy efficient measures (EEMs) with their specific energy savings, capital costs and CO_2 emission reduction together with 2020 production of the surveyed cement plants(Galitsky et al., 2008) (Institute for Industrial Productivity, 2022) (Schorcht et al., 2013)

No.	EEMs	2020 production (Mt/year)	Electrical Energy Savings (kWh/t-output)	Fuel Savings (GJ/t-output)	Primary Energy Savings (GJ/t-utput)[b]	CO_2 Emission Reductions (kg CO_2/t-output)[a]	Capital Cost (USD/t-output)	Annual additional O&M cost (USD/t-output)	Share of production capacity to which measure is applied
	Raw material preparation section			t –output = tonne of raw meal					
1	Raw Meal Process Control	8.614	0.9	0	0.004	0.005	0.3	0	62%
2	Raw Meal Blending (Homogenizing) Systems	8.614	1.8	0	0.009	0.011	3.7	0	50%
3	High efficiency Roller Mills	8.614	6.5	0	0.032	0.039	5.5	0	24%
4	High efficiency separators and classifiers	8.614	3.25	0	0.016	0.02	2.2	0	12%
5	Efficient transport system	8.614	2	0	0.010	0.012	3	0	15%
6	Installation of 3-fan system with a separate mill fan to take care of vertical roller mill operation	8.614	1.86	0	0.009	0.011	0.959	0	5%
	Fuel preparation section			t–output = tonne of cement					
7	New Efficient Coal Separator for Fuel Preparation	6.731	0.26	0	0.356	0.002	0.01	0	22%
8	Roller Mills for Fuel Preparation	6.731	1.47	0	2.014	0.009	0.05	0	68%
	Clinker making and cooling section			t –output = tonne of clinker					
9	Low temperature Waste Heat Recovery for power generation	5.423	30	0	0.148	0.18	1828USD /kW	0.007	30%
10	High-Efficiency Grate Coolers	5.423	-4.5[c]	0.18	0.158	17.001	5	0.11	28%
11	Optimized Heat Recovery in Clinker Cooler	5.423	-2[c]	0.11	0.100	10.394	0.2	0	17%
12	Energy management and process control systems	5.423	0.45	0.11	0.112	10.409	1	0	28%
13	Installation or Upgrading of a Pre-heater to a Pre-heater/Pre-calciner Kiln for Clinker Making in Rotary Kilns	5.423	0	0.4	0.4	37.84	18.7	-1.1	21%
14	Increasing Number of Pre-heater Stages in Rotary Kilns from 5 to 6 stage	5.423	-1.17[c]	0.11	0.104	10.399	2.79	0	59%
15	Modification of clinker cooler (use of Mechanical flow regulator)	5.423	0	0.07	0.07	6.622	0.489	0	10%
16	Replacing Vertical Shaft Kilns with New Suspension Pre-heater/Pre-calciner Kilns	5.423	0	2.4	2.4	227.04	18.7	1.1	4%
17	Kiln Combustion System Improvements for Clinker making	5.423	0	0.18	0.18	17.028	1	0	4%
18	Improved Refractories for Clinker Making	5.423	0	0.26	0.26	24.596	1.71	0	42%

	Finish grinding section			t –output = tonne of cement					
19	Use of Vertical Roller Mills	6.731	16.7	0	0.082	0.100	5	0	68%
20	High-Efficiency Separators/Classifiers for Finish Grinding	6.731	4	0	0.020	0.024	2	0	12%
21	Process Control and Management	6.731	3.25	0	0.016	0.020	0.5	0	35%
22	High-pressure roller press as pre-grinding to ball mill	6.731	16	0	0.079	0.096	5	0	68%
23	Improved Grinding Media for Ball Mills	6.731	4	0	0.020	0.024	0.7	0	30%
	General Utility systems			t –output = tonne of cement					
24	High-Efficiency Motors and Drives	6.731	3	0	4.11	0.018	0.22	0	30%
25	Adjustable or Variable Speed Drives	6.731	8	0	10.96	0.048	1	0	30%
26	High-Efficiency Fans	6.731	0.4	0	0.548	0.002	0.01	0	30%
	Product & Feedstock Changes			t –output = tonne of cement					
27	Blended cement production	6.731	-8.9[c]	2.19	2.146	211.063	0.72	-0.06	5%
28	Limestone cement production	6.731	3.3	0.28	0.296	27.012	0.18	0	5%

[a] CO_2 emission reduction is calculated using emission factor for coal combustion and emission factor for the Ethiopian power grid (IPCC, 2006)(United Nations Framework Convention on Climate Change [UNFCCC], 2013) This CO_2 emission reduction is due to reduced energy use.

[b] Primary energy is calculated based on the Ethiopian power grid efficiency including transmission and distribution losses.

[c] the negative values for electrical energy saving indicates that even though the application of this measures saves fuel, it will increase electricity consumption. However, the total primary energy saving of this measures are positive.

4.2.2 Electrical Energy Conservation Supply Curve

Table 4.4 presents the cost of conserved energy (CCE), energy saving and associated CO_2 emission reduction potentials of the seventeen electrical energy efficiency measures analyzed in the study, arranged by their CCE in ascending order. As depicted in the electrical energy conservation supply curve (Figure 4.5), eight of these energy efficiency measures in the EECSC are positioned below the average electricity unit price line for the surveyed plants in 2020. This indicates that the cost to invest in saving 1 MWh of electrical energy is lower than the expense of purchasing 1 MWh at the current electricity price, establishing these measures as cost-effective solutions for the studied cement plants. The combined annual average cost-effective electrical energy saving potential of these measures for Ethiopian cement plants in the production year 2020 amounts to 98.7 GWh, constituting approximately 11.5% of the plants' electrical energy consumption during the same period. Furthermore, the total electrical energy saving potential attributed to all measures examined in the study equals 284 GWh, which corresponds to around 33% of the annual electrical energy consumption of the surveyed plants.

Table 4.4: Electrical energy efficiency measures of the surveyed cement plants ranked by their CCE

CCE Rank	Electrical Energy Efficiency Measures (EEMs)	Electrical Energy Saving Potential (GWh)	Cost of Conserved Energy (USD/MWh-Saved)	CO_2 Emission Reduction (tonne)
1	High-Efficiency Fans	0.8	7.5	4.9
2	Roller Mills for Fuel Preparation	6.7	10.2	40.4
3	New Efficient Coal Separator for Fuel Preparation	0.4	11.5	2.3
4	High-Efficiency Motors and Drives	6.1	22.0	36.4
5	Adjustable or Variable Speed Drives	16.2	37.5	96.9
6	Process Control and Management in cement grinding	7.7	46.2	45.94
7	Improved Grinding Media for Ball Mills	12.1	52.5	72
8	Waste Heat Recovery Power Generation (WHRPG)	48.8	62.8	292.8
9	High-pressure roller press as pre-grinding to ball mill	73.2	93.8	439.4
10	Raw Meal Process Control	4.8	100.0	28.8
11	use of Vertical Roller Mills for finish grinding	76.4	107.8	458.6
12	High-Efficiency Separators/Classifiers for Finish Grinding	3.2	150.0	19.4
13	Installation 3-fan system with a separate mill	0.80	154.68	4.81
14	High efficiency separators and classifiers	3.36	203.08	20.16
15	Use of High efficiency Roller Mills	13.44	253.85	80.63
16	Efficient transport system	2.58	450.00	15.51
17	Raw Meal Blending	7.75	616.67	46.52

It can be observed from Table 4.4 that that the top three cost-effective electrical energy efficiency measures are: the application of high-efficiency fans, efficient roller mills for coal grinding, and new efficient coal separators for fuel preparation. However, the energy saving potential achieved by these measures is not substantial compared to other cost-effective measures. Conversely, implementation of waste heat recovery power generation plants, application of variable speed drives, and improving grinding media for ball mills emerge as the three cost-effective measures with the highest potential for electrical energy savings. On the other hand, as can be seen from Figure 4.5, more than half of the selected electrical energy efficiency measures (EEMs) aren't economically viable for the studied cement plants. One main reason could be attributed to the fact that Ethiopia's power grid is state-owned and regulated by the government, resulting in substantial subsidies and minimal electricity unit prices. Consequently, this subsidized and cheap electricity price fails to incentives investment in the adaptation of energy-efficient technologies and measures within energy-intensive sectors. Therefore, the findings of this research could serve as a valuable insights for shaping more effective energy policies. Regarding CO_2 emissions, the power grid heavily relies on renewable energy sources, primarily hydropower, which accounts for over 90% of the share. Thus, implementing electrical energy efficiency measures at Ethiopian cement industries will have negligible impact on the overall CO_2 emission reduction potential in the sector.

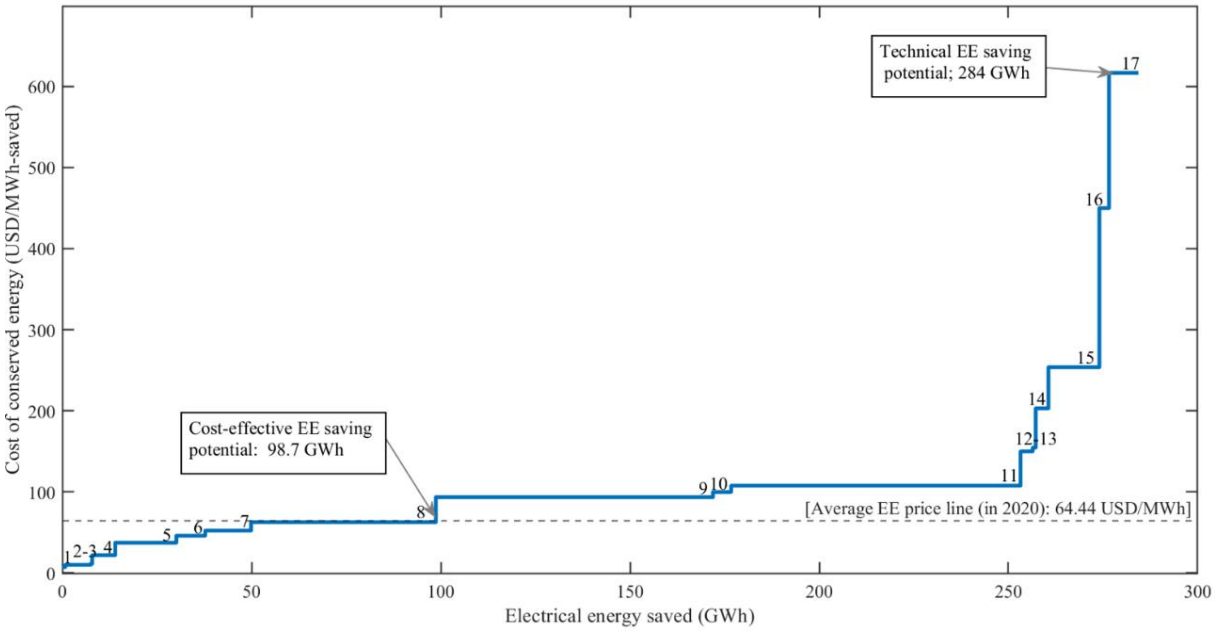

Figure 4.5: Electrical energy conservation supply curve (ECSC) of the studied cement plants.

4.2.3 Fuel Conservation Supply Curve

The evaluation findings of the fuel efficiency measures, ranked in ascending order based on their cost of conserved energy (CCE), along with their fuel saving and CO_2 emissions reduction potential, are presented in Table 4.5. Eleven energy efficiency measures have been assessed and included in the FCSC. As depicted in Figure 4.6, ten of these energy efficiency measures positioned below the annual average fuel price line for the surveyed cement industries in 2020. For these measures, the cost of investment required to save 1 GJ of fuel is lower than the expense of purchasing 1 GJ of fuel at the current price, rendering them cost-effective solutions for the studied cement plants. As noted in Table 4.5, considering the production of blended cement production with a 5% share (measure number 27 in Table 4.3) is the most cost-effective measure, and ranks second in terms of fuel savings among all other measures. On the other hand, improving refractories for clinker making (measure number 18 in Table 4.3) exhibits the highest fuel saving and CO_2 emission reduction potential among all measures examined in the study.

Table 4.5: Fuel efficiency measures of the surveyed cement plants ranked by their CCE

CCE Rank	Fuel Efficiency Measures (EEMs)	Fuel Saving Potential (TJ)	Cost of Conserved Energy (USD/GJ)	CO_2 Emission Reduction (kt)
1	Blended cements (with 5% share)	583	0.1	55.2
2	Limestone cement (with 5% share)	81.4	0.2	7.7
3	Optimized Heat Recovery in Clinker Cooler	92.2	0.6	8.7
4	Kiln Combustion System Improvements for Clinker making	39	1.7	3.7
5	Improved Refractories for Clinker Making	592	2	56
6	Modification of clinker cooler (use of Mechanical flow regulator)	38	2.1	3.6
7	Energy management and process control in kiln systems	167	2.7	15.8
8	Kiln Combustion System Improvements for Clinker making	521	2.80	49.3
9	Increasing Number of Pre-heater Stages in Rotary Kilns from 5 to 6 stage	333	8.05	31.5
10	High-Efficiency Grate Coolers	243	10.1	23
11	Installation/Upgrading of a Pre-heater to a Pre-heater/Pre-calciner Kiln	456	11.3	43.1

As presented in Table 4.6, the combined annual average cost-effective fuel saving potential of these measures for the studied cement plants based on 2020 production amounts to 2.7 PJ, approximately equivalent to 12.5% of the plants' annual fuel consumption (21.6 PJ). Additionally, the collective technical fuel saving potential resulting from all selected measures is estimated to be 3.1 PJ, representing roughly 14% of the total fuel consumption of

the plants. Regarding CO_2 emissions, the associated annual average CO_2 emission reduction attributed to the cost-effective fuel measures is about 254 kilo tonnes (kt), covering approximately 5% of the total CO_2 emissions produced by the surveyed cement plants. Furthermore, the total annual average technical potential for CO_2 emission reduction stands at 298 kt, constituting about 6% of the total CO_2 emissions from these plants in 2020.

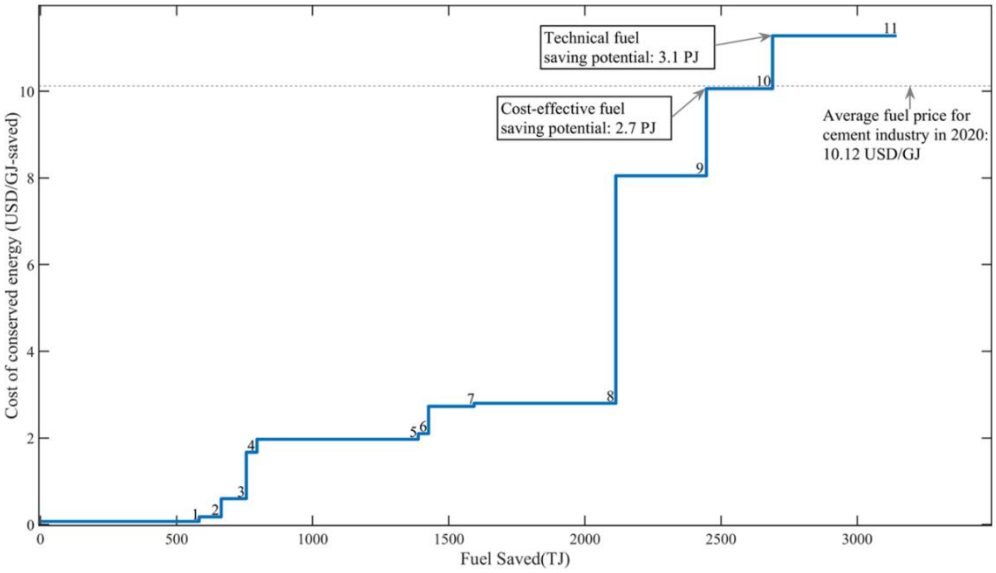

Figure 4.6: Fuel energy conservation supply curve (FCSC) of the surveyed cement plants

Table 4.6: Cost-effective and technical potentials for annual fuel saving and CO_2 emission

	Annual average fuel saving potential (PJ)		Annual average CO_2 emission reduction (Kt CO_2)	
	Cost-effective	Technical	Cost-effective	Technical
Saving potentials in 2020 production year	2.7	3.1	254	298
Share from all studied plants	12.5%	14%	5%	6%

4.2.4 Sensitivity Analysis

So far, the evaluation of cost-effective and technical energy efficiency improvement potentials for the studied cement plants have been conducted based on the base-case values of the parameters. The cost of conserved energy (CCE), energy savings, and CO_2 emission reduction potentials obtained by assessing the selected energy efficiency measures (see Chapter 3, section 3.3) relies on the assumption factors, including the discount rate, energy price, and capital cost. However, it's pertinent to examine how variations in these parameters can impact the cost-effectiveness of the measures analyzed in the study. Consequently, the outcomes of varying these parameters are presented in Tables 4.7, 4.8, and 4.9.

As expressed in equation 3.2 (Chapter 3, section 3.3), the discount rate (d) is directly related with the cost of conserved energy (CCE). A decrease or an increase in the discount rate will correspondingly reduce or increase the cost of conserved energy, potentially influencing the cost-effectiveness of energy efficiency measures. Table 4.7 illustrates the impact of varying the discount rate on the cost-effective energy savings and associated CO_2 emission reduction potentials of the EEMs while keeping other parameters constant. When the discount rate decreases from 30% to 20%, electrical energy efficiency measure 22 (utilizing high-pressure roller press as pre-grinding to ball mill) and fuel efficiency measure 13 (installation/upgrading of pre-heater to a pre-heater & pre-calciner kiln) become cost-effective with cost of conserved energy values of 64.1 USD/MWh and 6.8 USD/GJ respectively. Consequently, the combined cost-effective electrical energy saving potential increases from 98.7 GWh to 172 GWh, and the cost-effective fuel saving potential increases from 2.7 PJ to 3.1 PJ.

Conversely, when the discount rate shifts from 30% to 35%, electrical energy efficiency measure 9 (implementation of waste heat recovery power generation) and fuel efficiency measure 10 (using high-efficiency grate cooler) become non-cost-effective measures with cost of conserved energy values of 73.5 USD/MWh and 11.7 USD/GJ respectively. As a result, the combined cost-effective electrical energy saving potential decreases from 98.7 GWh to 49.9 GWh, and the cost-effective fuel saving potential decreases from 2.7 PJ to 2.4 PJ.

Table 4.7: Variations of cost-effective energy saving potential and CO_2 emission reduction at different discount rates (d)

Discount Rate (%)	Electrical Energy			Fuel		
	Cost-effective Energy Saving (GWh)	Cost-effective CO_2 Emission Reduction (kt CO_2)	Cumulative CCE (USD/MWh-saved)	Cost-effective Energy Saving (PJ)	Cost-effective CO_2 Emission Reduction (kt CO_2)	Cumulative CCE (USD/MWh-saved)
20%	172	1.03	253.1	3.1	298	27.84
25%	98.7	0.59	211.1	3.1	298	34.74
30% (base case)[a]	98.7	0.59	250.2	2.7	254	30.22
35%	49.9	0.23	219.3	2.4	231	23.51

[a] 30% discount rate is the base case which is used for the main analysis in this study (Hasanbeigi, Price, et al., 2010) (Hasanbeigi et al., 2011)

The unit price of energy can significantly impact the cost-effectiveness of energy efficiency measures. A higher energy price would render more energy-saving measures cost-effective. Table 4.8 illustrates the variation in cost-effective energy-saving and CO_2 emission reduction potentials of these measures under different energy price scenarios while keeping other

parameters constant. It shows that, a 50% increase in the energy unit price makes electrical energy efficiency measure 22 (utilizing high-pressure roller press as pre-grinding to ball mill) and fuel efficiency measure 13 (installation/upgrading of pre-heater to a pre-heater & pre-calciner kiln) cost-effective. Conversely, a 5% decrease in the energy unit price makes electrical energy efficiency measure 9 (application of waste heat recovery power generation plant) and fuel efficiency measure 10 (using high-efficiency grate cooler) non-cost-effective measures.

This analysis proves that most of the selected electrical energy efficiency measures cannot achieve cost-effectiveness with only a small increment in the base-case energy price. This is likely due to the fact that the Ethiopian electricity tariff is subsidized by the government and remains minimal. In general, this low energy price could discourage investment in adopting new power-saving measures in energy-intensive sectors. Consequently, it's imperative for the government or policymakers to develop mechanisms aimed at eliminating industrial energy price subsidies to facilitate the better implementation of potential EEMs in the cement sector.

Table 4.8: Variations of cost-effective energy saving potential and CO_2 emission reduction at different energy unit prices

	Electrical Energy (EE)			Fuel		
Scenario Energy Price (EP)	Cost-effective Energy Saving (GWh)	Cost-effective CO_2 Emission Reduction (kt CO_2)	Cumulative CCE (USD/MWh-saved)	Cost-effective Energy Saving (PJ)	Cost-effective CO_2 Emission Reduction (kt CO_2)	Cumulative CCE (USD/GJ-saved)
EP(-5%)	49.9	0.3	187.4	2.4	231	20.2
EP(Base case)[a]	98.7	0.6	250.2	2.7	254	30.2
EP (5%)	98.7	0.6	250.2	2.7	254	30.2
EP (10%)	98.7	0.6	250.2	2.7	254	30.2
EP (20%)	98.7	0.6	250.2	3.1	298	30.2
EP (50%)	172	1	344			

[a] The base case energy prices are energy prices used in the main analysis in this study.

The specific capital cost (investment cost) of the measures listed in Table 4.3 may also be subjected to some variations, as the average cost derived from the industrial energy efficiency database is considered in this study. The cost of conserved energy (CCE) is directly related with the capital cost, as described in equation 3.3 (Chapter 3, section 3.3). Table 4.9 illustrates how changes in the capital cost of the measures can impact the cost-effective energy savings and CO_2 emissions reduction potentials of the measures, while keeping other parameters constant. If the base-case capital cost of the measures is decreased by 10%, all the fuel

efficiency measures included in the study will become cost-effective, resulting in a total fuel saving potential of 3.1 PJ and a CO_2 emissions reduction potential of 0.298 Mt. However, no additional cost-effective electrical energy saving measures are obtained. Whereas, if the capital cost of the measures is increased by 5% from the base-case value, electrical energy efficiency measure 9 and fuel efficiency measure 10 will no longer be cost-effective.

Table 4.9: Variations of cost-effective energy saving potential and CO_2 emission reduction at different specific capital costs

Capital Cost (CC)	Electrical Energy (EE)			Fuel		
	Cost-effective Energy Saving (GWh)	Cost-effective CO_2 Emission Reduction (kt CO_2)	Cumulative CCE (USD/MWh-saved)	Cost-effective Energy Saving (PJ)	Cost-effective CO_2 Emission Reduction (kt CO_2)	Cumulative CCE (USD/GJ-saved)
CC–10%	98.7	592	225.2	3.1	298	37.2
CC–5%	98.7	592	237.7	2.7	254	28.8
CC (base case)	98.7	592	250.2	2.7	254	30.2
CC+5%	98.7	592	262.7	2.4	231	21.2
CC+10%	49.9	299	206.1	2.4	231	22.1

[a] the base case capital cost is the capital cost used in the main analysis in this study.

4.3 The Energy Demand Flexibility Potential in Cement Industries

The methods outlined in Chapter 3, section 3.4 aim to demonstrate the potential for demand flexibility in the cement industry and to suggest a system for managing/scheduling the flexible electrical loads of industrial customers to achieve an optimal electrical power flow through Demand Response (DR Its goal is to demonstrate the mutual benefits of DR for both consumers and the power grid. Thus, section 4.3.1 presents the available demand flexibility potential of the case study cement plants. Section 4.3.2 demonstrates the optimal operation/scheduling of each cement plant using the model developed in Chapter 3, taking into account all relevant constraints.

4.3.1 Demand Response Potential of the Ethiopian Cement Plants

Three cement plants with a combined capacity of 6 Mt cement production capacity have been selected to be used as a case study for this specific objective. These plants were chosen based on their high annual cement production performance, with a capacity factor of 70% or more. In 2020, these plants achieved an average production capacity factor of approximately 83%. Their average electrical energy intensity was 121 kWh/tonne of cement. Within this, 40% was

attributed to the cement grinding section, equating to 48 kWh/tonne of cement, and 26% to the raw meal preparation section, which amounted to 31 kWh/tonne of cement, equivalent to 24 kWh/tonne of raw meal (taking the average ratio of raw meal to cement production of 1.3). These two sections constitute about 66% of the total electrical energy consumption of the selected plants. The key processing steps/machines' average and maximum operating speeds, estimated using the equations specified in Chapter 3, section 3.4.1 are presented in Table 4.10, along with their respective specific electrical energy consumption. The semi-finished/finished products of the plants, such as crushed limestone, raw meal, clinker, coal, and cement were obtained from the cement plants' catalog.

Table 4.10: Summary of data and key assumptions required to estimate demand flexibility

Main steps/machines	Output	Load hours (h/yr)	Production (kt/yr)	Average operating speed (kt/h)	Maximum operating speed (kt/h)	EE consumption (kWh/t)
Crushers	crushed limestone	3, 744	6,626	1.77	2.13	1.2
Raw mills	raw meal	7,200	6,626	0.92	1.11	24
Pre-heaters, kilns & coolers	clinker	7,920	4, 180	0.53	0.64	40
Cement mills	cement	7,200	5,089	0.71	0.85	48
Coal mills	coal	7,560	740	0.10	0.12	33
Packaging & Loading	cement	6,480	5,089	0.79	0.95	2.4

Average operating speed is based on the actual production; maximum operating speed is based on the installed capacity, EE: electrical energy.

Using equations stated in Chapter 3, section 3.4.1, alongside the data provided in Table 4.10, the available potentials of demand flexibility for the primary sections of the cement process are estimated. Figure 4.7 illustrates the technical demand flexibility potential of these processing steps/machines. According to the findings, cement milling, and raw milling sections exhibit higher flexibility potential of 275 and 179 MWh per day, respectively (including both load curtailment and load shifting). These figures represent 15.5% and 10% of the total daily energy consumption of the analyzed cement plants, respectively. As shown in Table 4.11, the cumulative demand flexibility potential of the primary processing machines totals approximately 495 MWh per day, constituting roughly 28% of the total daily electrical energy consumption of the examined cement plants.

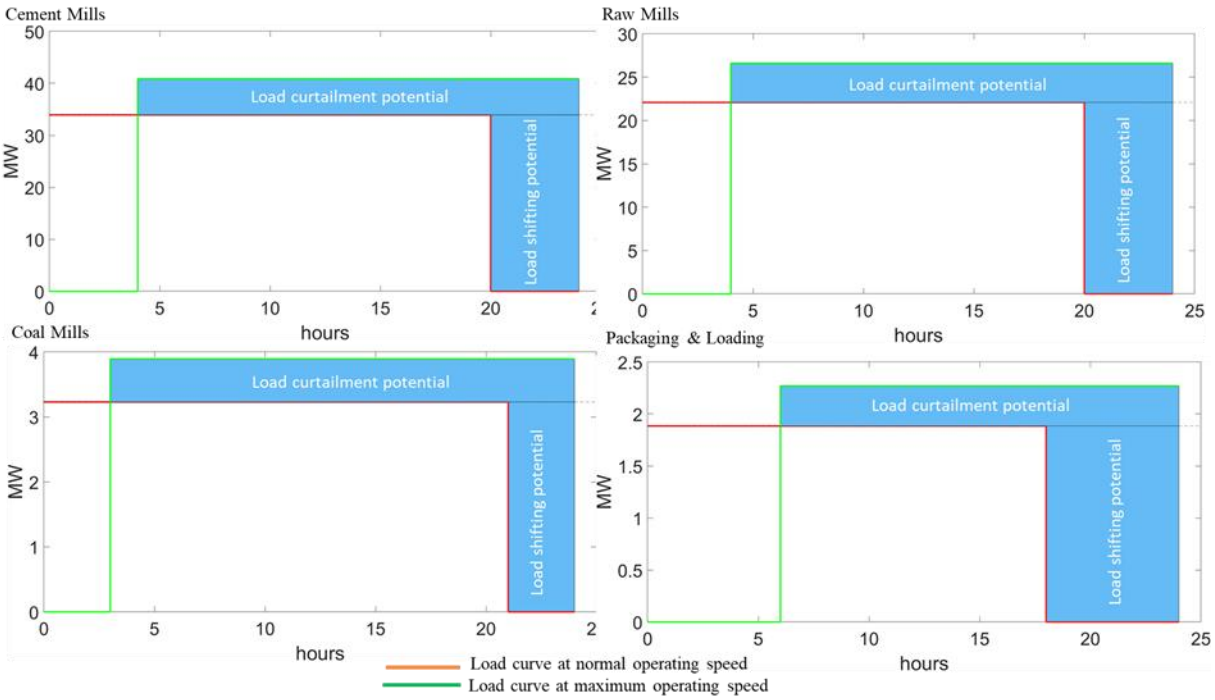

Figure 4.7: Daily load shift potentials of the main processing sections

In this section, the available DR potential is estimated by considering three cement plants with a combined annual capacity of 6 million tons of cement production. Whereas, in Ethiopia, there exist about 20 cement plants with a total production capacity of 13 million tons per year (Mossie et al., 2023). Hence, the demand flexibility potential for the Ethiopian cement sector could be greater than the value presented here. The demand flexibility potential estimated from the cement plants can be leveraged as an input to the power grid to assist other users at peak times of the day, or to address imbalances between power demand and supply. However, for this to be feasible, suitable incentives and/or electricity pricing mechanisms must be developed by the grid operator or policymakers. Moreover, it should be technically and economically viable for these customers to participate in demand response programs. To determine the feasible portion of DR obtained from each cement plant while adhering to all constraints, including energy cost, daily production targets, maximum machine operating hours, and hourly & daily power demand limits, an optimal model has been developed in Chapter 3, section 3.4.2 and tested with case study data in section 4.3.2.

Table 4.11: The average demand flexibility potential of the selected cement plants

Processes	Daily demand flexibility potential (MWh/day)	Total demand at 2020 production, CF=83% (MWh/day)	Total demand at max. production capacity, CF=100% (MWh/day)
Raw mills section	178.8	441.7	532.2
Cement mills section	274.7	678.5	817.5
Coal mills section	23.6	67.8	81.7
Packaging & loading section	18.3	34	41
Total	495	1222	1472

4.3.2 Demand Response at Optimal Operation/Scheduling of the Case Study Plants

The initial step to demonstrate the performances of the developed MINLP model, along with case study findings, involves gathering essential data from the designated cement plants (refer to Appendix B). Seven main processing machines/loads for each case study cement plants are incorporated in the model, comprising five flexible loads, and two fixed loads. From the hourly load curve of the Ethiopian power grid (refer to Chapter 3, section 3.6), three periods are considered: off-peak period (23:00 – 6:00), shoulder period (7:00 – 17:00) and peak period (18:00 – 22:00). The proposed MINLP model has been customized for each cement factory, and feasible solutions are obtained using a GRG nonlinear solver. Subsequently, an optimal operation/schedule has been achieved for each cement factory which can minimize the daily cost of energy use by the factory on the one hand, and the peak electrical energy demand and emission of the national power grid on the other hand. The hourly load curves of the plants depicted in Figures 4.8, 4.9, and 4.10 reveal that the proposed model effectively fulfills the study objectives.

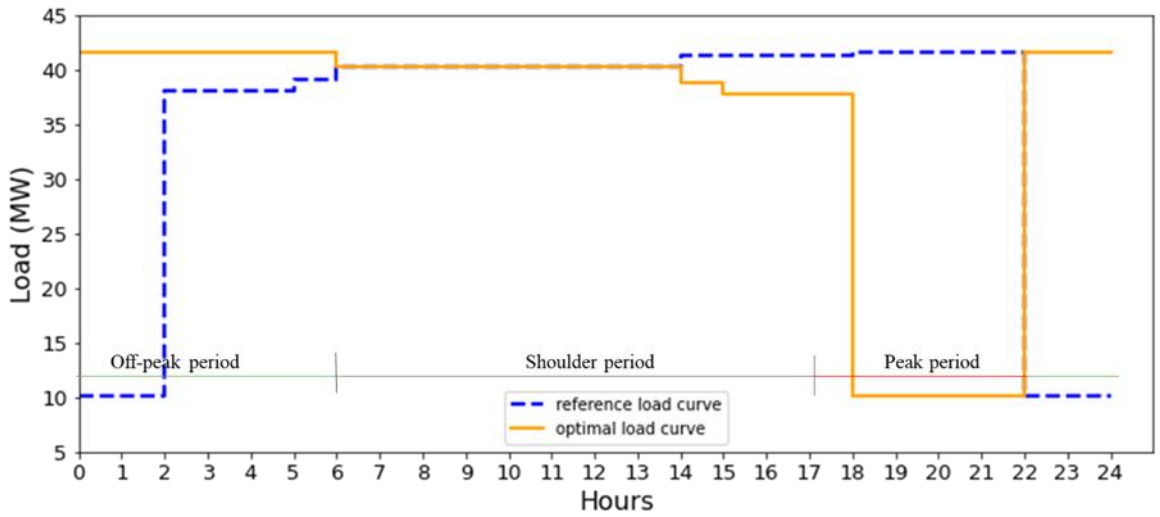

Figure 4.8: Hourly electrical load curves for cement plant-1before and after applying the model

Figure 4.8 illustrates the hourly load curves of the first case study cement plants (Cement Plant -1) both before and after adapting the model. As can be observed from the figure, initially, without the proposed model, the maximum load during the peak period stands at 41.7 MW, with corresponding energy consumption totals of 208 MWh, 447 MWh, and 194 MWh during peak, shoulder, and off-peak periods of the day, respectively. When the model is adapted, its electrical load during the peak period is reduced to 10.2 MW, resulting in revised energy usage of 78.5 MWh, 437 MWh, and 333 MWh during peak, shoulder, and off-peak periods, respectively. Similarly, in Figure 4.9, the situation at the second case study plant (Cement Plant -2) is depicted. Initially, the plant registers a peak load of 39 MW, accompanied by energy consumption values of 192 MWh, 315 MWh, and 78 MWh during peak, shoulder, and off-peak periods, respectively, before the model adaptation. Subsequently, after considering the model, the peak load is diminished to 9.8 MW, leading to revised energy consumption figures of 49 MWh, 231 MWh, and 306 MWh during peak, shoulder, and off-peak periods, respectively.

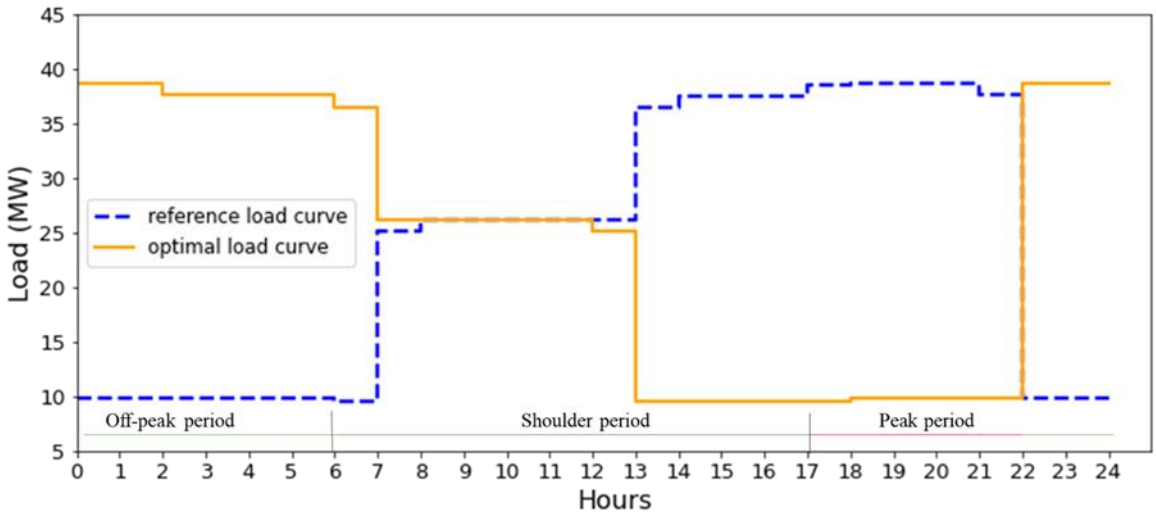

Figure 4.9: Hourly electrical load curves for Cement Plant-2 before and after applying the model

Figure 4.10 presents the hourly load curves of the third case study cement plant (Cement Plant -3), before and after adapting the model. Before the model adaptation, the plant's peak demand is approximately 22 MW, with energy consumption values of 108 MWh, 177 MWh, and 57 MWh during peak, shoulder, and off-peak periods, respectively. Following the adaptation of the proposed model, the peak demand during the peak period reduces to 5.6 MW, with corresponding energy consumption values of 29 MWh, 143 MWh, and 173 MWh during peak, shoulder, and off-peak periods, respectively. It's noteworthy that the overall daily production and energy consumption remain consistent in both cases.

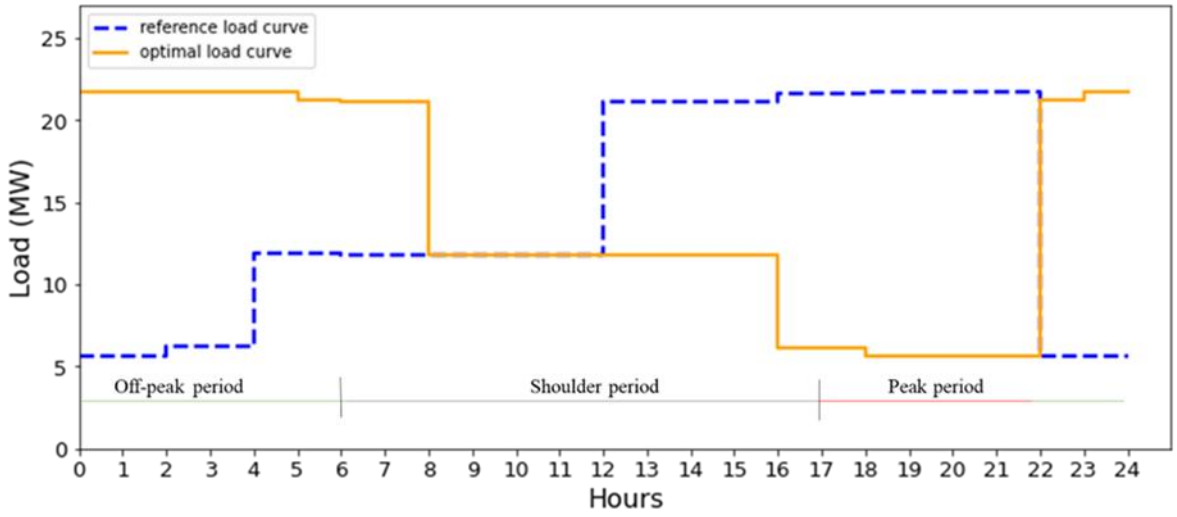

Figure 4.10: Hourly electrical load curves for Cement Plant-3 before and after applying the model

Hence, it is demonstrated that by applying the proposed model in the case study cement plants, there is a significant reduction in the maximum loads during the peak period of the day. Explicitly, there is a decrease of approximately 76% in the first plant, 75% in the second plant, and 74% in the third plant. The variations mainly come from the differences in their reference schedules, as they vary due to the daily production and machine operating capacities. The combined load of the three case study cement plants is about 102 MW. By applying the proposed model, it is diminished to 26 MW, resulting in a saving of approximately 76 MW in demand during the peak period the day. Similarly, the total energy consumption during the peak period is reduced by 62% in the first plant, 75% in the second plant, and 74% in the third plant. The model shifts the reduced loads during peak period to the off-peak and shoulder periods of the day. Accordingly, the peak loads of the plants are minimized, while their off-peak loads are maximized. As evidenced in Table 4.12, the objective function is minimized for all cement plants, indicating the successful reduction of the load during the peak period and the maximization of the plants' electrical load during the off-peak period by adapting the developed model. Consequently, one of the primary goals of DSM, which is to minimize the peak period electrical loads of the industrial customer by shifting them to the off-peak periods in order to flatten the national power grid load curve, has been achieved. It is evident, therefore, that the proposed model mitigates the adverse impact on grid stability stemming from one of the most energy-intensive industries, cement production.

Table 4.12: Optimization indicators, loads at peak period and cost of energy

Case study plants	Objective function value		Maximum load at peak period (MW)		Cost of energy per day (USD)	
	At Initial state	With the proposed model	At Initial state	With the proposed model	At Initial state	With the proposed model
Plant -1	2.79	1.49	41.7	10.2	59, 713	54, 343
Plant -2	4.26	1.01	39	9.8	43, 256	35, 842
Plant -3	3.54	1.04	21.7	5.6	25, 062	21,189
Aggregate			102.4	25.6		

As clarified in Chapter 3, the electricity tariff on the Ethiopian power grid is a flat rate, which fails to incentivize customers to adopt demand response (DR) techniques. So, to examine the cost savings in energy consumption for the case study plants with the proposed model, the average time-of-use (TOU) tariff structure of the East African region is used for both the reference schedule and the proposed schedule, with rates of 0.09 USD per kWh for peak, 0.07 USD per kWh for shoulder, and 0.05 USD per kWh for off-peak periods of the day (see Table 1.1), based on March 2023 data. Accordingly, the cost of consumed electrical energy for a day decreases by 9% in Plant -1, 17% in Plant -2, and 16% in Plant -3 in the new schedule. These findings prove that the developed model can effectively reduce the cost of energy consumption in cement plants through the implementation of demand response strategies. Thus, a substantial reduction in energy costs has been achieved when comparing the cost of daily energy consumption between the proposed optimal operation schedule and the previous operation schedule (refer to Table 4.12).

4.4 Techno-economic evaluations of Waste heat recovery (WHR) power plants

The purpose of this study is to investigate the potential for electricity generation from waste heat in the Ethiopian cement industry by considering the implementation of onsite waste heat recovery power plants (WHRPPs). To identify the most feasible option for the designated case study cement plant and to determine the average energy cost generated by the WHRPPs, the life cycle costs (LCC), levelized cost of energy (LCOE), and net present values (NPV) of the three alternative WHRPPs available in the market are evaluated. The expected power output capacity of the WHRPP is estimated at various system efficiencies and different rates of heat available for recovery from the waste heat source. As illustrated in Figure 4.11, the electricity generation capacity of the WHRPP varies depending on the system efficiency and the rate of the available waste heat to the system. Accordingly, by using the approaches and equations described in Chapter 3, section 3.5.2, and the parameters depicted in Table 3.4, it is

determined that the annual average rate of heat available in the preheater exhaust gas and clinker cooler hot air for electricity generation is about 22% of the annual heat input rate for clinker production, resulting in an annual average heat rate of 44.4 MW in the WHR system (refer to Table 3.4). The system efficiencies for the three types of WHRPPS are assumed to be 20%, 24%, and 26% for SRC-based, ORC-based, and KRC-based WHRPPs, respectively. Consequently, the power output capacities of the three options become 8.9 MW, 10.7 MW and 11.5 MW respectively.

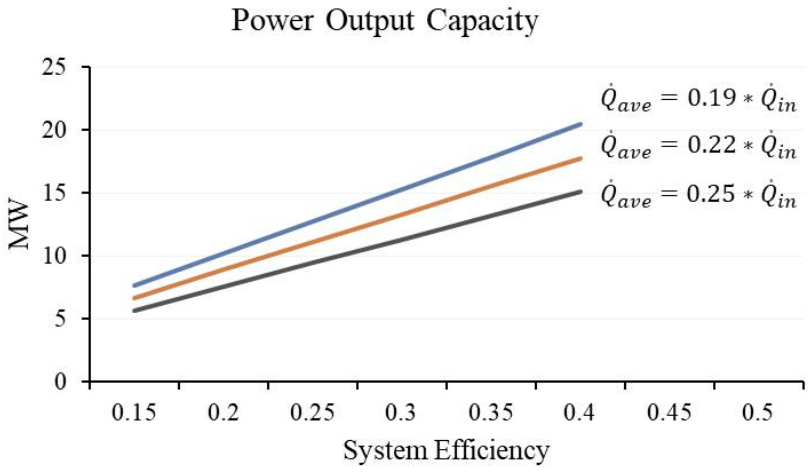

Figure 4.11: Power output capacity with respect to efficiency and available heat rate

By using the provided information and the approaches described in section 3.5.3, the total expenses and revenues at the end of the lifetimes of each option are illustrated in Table 4.13. The expected power capacity and the annual average energy generation potential of each WHRPPs are estimated. Consequently, the total life cycle costs (LCC), and the total revenues obtained (REG) are determined. Then, the levelized cost of energy (LCOE) and the net present values (NPV) at the end of the lifetimes (25 years) of the plants for each WHRPPs option are finally estimated. Accordingly, for steam RC-based WHRPP, the LCOE and NPV are about 0.04 USD/kWh, and 0.35 million USD, respectively. While for ORC-based WHRPP, about 0.06 USD/kWh, and -3.2 million USD are obtained for LCOE, and NPV, respectively. For the third option, Kalina RC-based WHRPP, 0.06 USD7kWh, and -4.7 million USD are obtained for LCOE, and NPV, respectively.

Table 4.13: Results obtained for the three types of WHRPPs considered

No.	Parameters	SRC-based WHRPP	ORC-based WHRPP	KRC-based WHRPP
1.	Capital Cost (Million USD)	9.8	14.9	17.3
2.	Total Operation & Maintenance Cost (Million USD)	19.3	29.3	34.0
4.	Total Major Replacement Cost (Million USD)	3.9	5.9	6.9
5.	Total Life Cycle Cost (LCC) (Million USD)	33.0	50.1	58.2
6.	Salvage Value (Million USD)	0.9	1.4	1.6
7.	Cost of Energy Saved (Million USD)	136	163	176
8.	Total revenue (REN) (Million USD)	137	164	178
9.	Net Present Value (NPV) (Million USD)	0.35	-3.2	-4.7
9	Leveized cost of energy (LCOE) (USD/kWh)	0.04	0.06	0.06
10	Payback Periods (years)	15	-	-

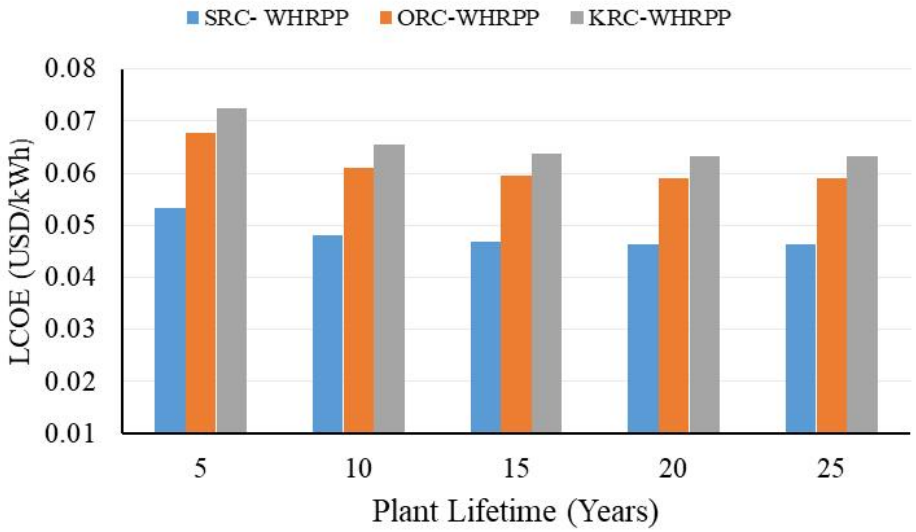

Figure 4.12: Levelized cost of energy for the three WHRPP options at different lifespan

Figure 4.12 depicts the levelized cost of energy (LCOE) for the three alternatives of waste heat recovery power plants (WHRPPs) across various lifetimes (years). As the lifetime period of the plants are shorten, the LCOE become higher, making all the options infeasible for investment. At the assumed lifetime of 25 years, the LCOE values for SRC-based, ORC-based, and KRC-based WHRPP technologies are about 0.04 USD/kWh, 0.06 USD/kWh, and 0.06 USD/kWh, respectively. This highlights that SRC-based WHRPP exhibits the lowest cost of energy generation compared to the other options. Meanwhile, Figure 4.13, illustrates the net present values (NPV) of the three categories of WHRPPs over different lifetimes, indicating the investment impractical for all options for shorter lifespans than 25 years. Notably, SRC-based WHRPP exhibits a positive NPV of 0.35 million USD at a plant lifespan of 25 years. Conversely, the other WHRPP options demonstrates negative NPVs, with values

of -3.2 and -4.7 million USD, respectively. Despite the technical potential of all three options to generate electricity from wasted heat, with respective power capacities of 8.9 MW, 10.7 MW, and 11.5 MW for SRC-based, ORC-based, and Kalina RC-based WHRPP options, only SRC-based WHRPP emerges as both technically and economically viable for the cement plant studied in Ethiopia. The estimated payback period for the investment in this feasible WHRPP option is 15 years.

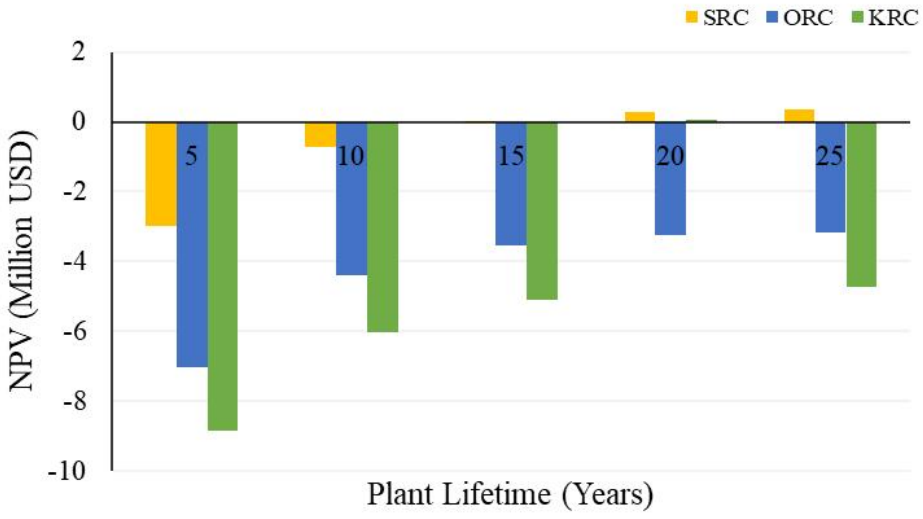

Figure 4.13: Net present values (NPV) of the three WHRPP options at different lifespan

The electrical power demand capacity of the case study cement plant is about 50 MW, from which the feasible SRC-based WHRPP with 8.9 MW capacity can cover about 18% of its demand, reducing the dependency of electricity consumption from the national grid. Thus, the energy loss in the factory is reduced such that the waste heat through the pre-heater exhaust gas and the clinker cooler air are now recovered and back to use, offering a significant energy savings. This result is inline with (Han et al., 2018) and (IFC, 2014) which states that through waste heat recovery onsite power plant, 20- 30% electricity need of a typical cement plant can be covered. In addition, WHR power plant can also reduce the associated CO_2 emissions of a cement plant due to electrical consumption from the grid. However, in this study, the Ethiopian power grid electricity emission factor is minimum with 0.006 kg CO_2 per kWh according to IPCC guide line. It is due to the fact that the energy mix in the Ethiopian grid is dominated by renewable energy sources, specifically hydropower with a share of more than 90% of the total. Still, an average emission reduction potential of 426 ton of CO_2 per year is achieved by the SRC-based WHRPP in the case study cement plant.

However, during peak periods, the Ethiopian power grid energized a diesel power plant and is on standby at other times of the day, constituting about 2% of the energy mix. When we consider the reduced electricity consumption of the cement plant during this period from the grid, substituted by the onsite WHRPP, the reduced CO_2 emissions during this period is significant as the emission factor of a diesel power plant is about 0.533 ton CO_2 per kWh according the IPCC guideline 2006, Chapter 2, stationary combustion (IPCC, 2006), and the UNFCCC methodological tool (United Nations Framework Convention on Climate Change [UNFCCC], 2013). Thus, taking 18:00 to 22:00 as peak hours of the Ethiopian power grid, an average emission reduction potential of 7.9 Mt of CO_2 per year is achieved by the SRC-based WHRPP in the case study cement plant. Therefore, the proposed WHRPP can enhance the overall energy efficacy and reduced the associated CO_2 emissions in the case study cement plant.

4.4.1 Sensitivity Analysis Considering Parameter Variations

The initial capital cost of the WHR power plant options, the discount rate and unit price of electricity assumed in this type of investment are the main crucial factors in determining the feasibility of implementing such systems. The data concerning these factors in this study are derived from secondary sources in the literature, meaning that fluctuations in these factors could impact the confidence of the technology options. Therefore, by adjusting some level of uncertainty associated with these parameters in the estimation equations, the following variations on the findings of the LCOE and NPV of the three WHRPP options are obtained. In addition, variations on the unit price of electricity taken in this study highly impact the NPVs of the plant options.

The discount rate considered in this study is 30%. However, the discount rate could vary depending on the situation of the country. Thus, it is demonstrated in Figure 4.14, (a) that as the assumed discount rate decreases from the base case value (30%) to 10%, the leveleized cost of energy of the three WHRPP technology options decreases from the base case value to 0.024, 0.03, and 0.032 for SRC, ORC, KRC-base waste heat recovery technology options respectively, making all options feasible for the case study cement plant with the net present values of 23.9, 23.7, and 23.9, million USD respectively.

Given the high inflation rate in Ethiopia, with an annual average of 15.3%, a nominal discount rate of 30% has been applied in this study. However, if inflation is assumed to be mitigated through government intervention, a real discount rate of 12% can be used. At this rate, the

levelized cost of energy for the three-waste heat recovery power plants becomes 0.025, 0.032, and 0.035 USD/kWh for SRC, ORC, and KRC respectively. This assumption makes all options viable for the Ethiopian case study cement plant, with net present values of 18.4, 17.46, and 17.25 million USD, respectively.

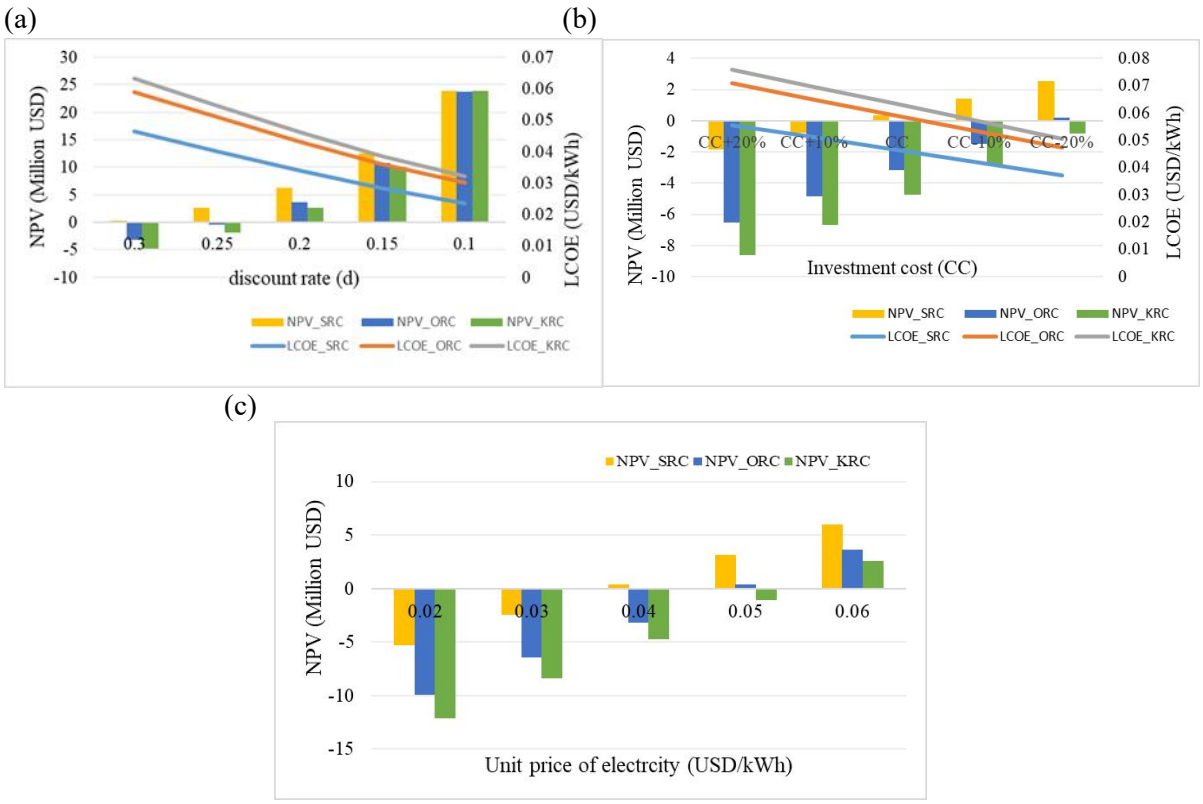

Figure 4.14: Variations of NPV and LCOE of the three WHRPP options from the base case values (a) NPV and LCOE vs discount rate, (b) NPV and LCOE vs investment cost, (c) NPV vs unit price of electricity

Similarly, when the initial capital costs of these plants increase from the base case value by 20%, the levelized cost of energy of the three options rises to 0.056, 0.071, and 0.076 USD/kWh, making all the options not feasible for the selected Ethiopian cement plant with net present values of -1.84, -6.52 and -8.61 million USD (refer to Figure 4.14, (b)). While by decreasing the base case capital costs by 20%, ORC-based WHRPP becomes feasible option with net present value of 0.85 million USD. When the unit price of electricity increases from the base case to0.06 USD/kWh, all the three WHRPP options become feasible with NPVs of 6.0, 3.6, and 2.6 million USD for SRC-based, ORC-based, and KRC-based WHRPP options, respectively (Figure 4.14, (c)). The conversion efficiencies and the percentage of heat losses by the pre-heater exhaust gas and clinker cooler are also factors that can influence the LCOE and NPV of these power plant technology options, however, they do not significantly affect the values obtained by the base case assumption. When the overall conversion efficiencies of

the plants and the percentage of waste increase from the bases values, the power capacities of the plants can increase from the values obtained from the bases cases assumptions, however, as the investment costs and the energy generation of the plants are directly related to the plant installed power capacity, their impact to the LOCEs and NPVs will be balanced.

Chapter 5: Discussion

The findings described in Chapter 4, address the demand side energy management strategies: energy efficiency measures, demand response strategies and onsite power generation potential applicable to the cement industry. The opportunities for energy saving and environmental mitigation, as well as the potential for energy demand flexibility and waste heat recovery power generation, have been evaluated in cement industries with case study verifications. Thus, the study approves that DSM can also contribute to energy supply security and environmental sustainability. The models developed and verified by data that the cement industry has a viable source of flexible demand for the power grid. However, the realization of the DSM strategies assessed in this study requires appropriate regulatory frameworks that create incentives for energy-intensive participants including the cement industry.

5.1 Comparison with Related Studies and International References

To validate the findings obtained in this study, Table 5.1 presents a summary of similar studies conducted on cement plants in different countries, which have investigated energy saving and climate mitigation potential in the cement industry. Njoku et al (Njoku et al., 2017) and Hasanbeigi et al. (Hasanbeigi, Price, et al., 2010) applied the BEST-Cement tool to examine the potential energy savings of their respective cement plants. According to the first study, an energy saving potential of 20-52% in thermal energy and 35-43% in electrical energy was obtained from the three Nigerian cement plants. In the second study, an average of 23% primary energy-saving potential was reported. Whereas, the current study indicates an average of 36% primary energy-saving potential across the seven Ethiopian cement plants. The variation in the number of energy efficiency measures considered in these studies is influenced by factors such as the type of cement plants under investigation and the implementation status of energy efficiency measures before the study period.

These studies employed same methods, the ECSC model, to evaluate the energy saving and CO_2 emission reduction potentials of various energy efficiency measures (EEMs) for cement plants. Their findings indicate that most of the fuel efficiency measures considered in these studies are cost-effective for the respective case study cement plants. However, the share of cost-effective savings of the electrical energy efficiency measures from their technical potential varies among the studies. For instance, results from Thai and Ethiopian cement industries showed that the share of cost-effective electrical energy saving potential of the evaluated measures is minimal relative to their technical saving potential. The primary reason

attributed to the fact that the price of electrical energy is relatively low and subsidized by the government in Thailand and Ethiopia.

These studies confirm that energy efficiency in the global industrial sector is significantly below the levels that are technically feasible and economically optimal. In line with this, the International Energy Agency (IEA) estimates in its report 'Technology Roadmap-Low-Carbon Transition in the Cement Industry 2018' that CO_2 emissions in the cement industry could decrease globally from 7% to 4% by 2050 through measures such as enhancing energy efficiency within the sector (IEA, 2021c). Similarly, the United Nations Industrial Development Organization (UNIDO, 2014) estimates that industries, in general, have the technical capacity to reduce their energy intensity by up to 26% and their emissions by up to 32%. These reductions could lead to significant decreases in total global energy consumption (by 8%) and CO_2 emissions (by 12.4%). Thus, keeping in mind that the EEMs priorities are site-specific, these references confirm that the findings of this study align with international perspectives. Therefore, the present study can contribute its part in promoting energy efficiency measures aimed at achieving more energy-efficient and environmentally friendly cement production on a broader scale. Furthermore, it can serve as a reference for stakeholders and policymakers in formulating effective policies for energy use and CO_2 abatement in this sector.

Table 5.1: Comparison summary of the findings with related studies

Sources	No. CPs (included)	Saving Potential (BEST-Tool)	No. EEMs (included)	ECSC Model Result			
				Cost-effective EE saving	Technical EE saving potential	Cost-effective Fuel saving	Technical Fuel saving potential
(Njoku et al., 2017)	3 (Nigerian CPs)	20-52 % TE 35-43 % EE	17	374,055 GJ of both	-	-	395,447 GJ of both
Hasanbeigi, Price, et al., 2010)	16 (China CPs)	23 % PE	34	16 %	40 %	8 %	8 %
(Morrow et al., 2014)	500 (India CPs)	-	22	83 TWh	89 TWh	1029 PJ	1029 PJ
(Hasanbeigi et al., 2011)	14 (Thai CPs)	-	47	8 %	51 %	16 %	19 %
In this Study	7 (Ethio. CPs)	36% PE	28	11 %	33 %	12 %	14 %

5.2 Reflections

As presented in Chapter 4, Section 4.1, the energy performance assessment indicates that an average energy-saving potential of about 36% is estimated. Through the adoption of identified potential energy efficiency measures, a significant share of annual energy savings have been achieved, about 33% of annual electrical energy and 14.5% of annual fuel consumption considering all measures included as explained in Section 4.2. However, the total available energy-saving potential has not been fully achieved in this study.This is because the study includes 28 potential energy efficiency measures and technologies that are not yet implemented in most Ethiopian cement plants. However, achieving the full 36% energy-saving potential may require additional measures beyond those considered in this study. Some energy-saving opportunities might not have been identified or evaluated due to data limitations or scope boundaries. Therefore, further investigation is needed to explore and assess additional energy efficiency measures, technologies, and best practices that could help realize the full energy-saving potential in the Ethiopian cement industry.

Additionally, the energy and environmental performance comparison at cemetn industries in Ethiopia and Sweden is presented in Section 4.1, The natural ambient temperature differences between Ethiopia and Sweden could indeed affect energy intensity, especially in industries with significant heating needs. Even small temperature variations can impact efficiency and energy use. In cross-country comparisons like this study, it may be important to account for these climatic differences. However, this study has not addressed this issue. Future study will note how Ethiopia's warmer climate may reduce heating/energy demands compared to colder regions like Sweden, influencing energy intensity and system performance.

The outcomes of the investigation conducted on the three cement plants as presented in Chapter 4, section 4.3, indicates that, on average, the model proposed through DR has the capability to minimize the electrical loads of the cement plants up to 25% during peak hours. This reduction is achieved by shifting the reduced electrical load to the off-peak hours of the power grid, without affecting the case study cement plants' daily production and energy consumption targets. The aggregate electrical power demand capacity of the studied cement plants is about 102 MW. Considering the broader context of the Ethiopian cement sector, which comprises around 20 cement plants, the total power demand capacity could exceed 300 MW. Hence, the potential reduction in electrical power demand by the sector during peak hours could be substantial, significantly influencing the overall peak demand reduction during

critical periods of the grid. Furthermore, the results reveal that the average cost of electricity consumption in cement plants can be lowered by 14% through the proposed schedule, taking Time-Of-Use (TOU) tariff structures into consideration. This underscores the effectiveness of TOU-based demand response in reducing electricity expenses by shifting energy consumption from peak to off-peak periods, thereby serving as a key incentive for industrial facilities to engage in TOU-based Demand Response programs.

In this study to validate the proposed model, three case study cement plants are included. It has been shown that their reference load curves are different as obtained from their energy utilization catalog, leading to different load curves for both at the reference schedule and at the proposed model schedule. This variation stems from the fact that, prior to implementing the proposed model, each plant followed its own operating schedule, driven solely by production demands, without factoring in energy optimization In their production. This confirms that energy usage in the Ethiopian cement sector is currently managed arbitrarily, impacting to grid instability.

Therefore, the electrical energy obtained from the grid can be optimally utilized through DR applications in the cement industry. In other words, if the Ethiopian power grid implements DSM strategies including TOU-based DR program, a substantial flexible electrical load can be derived from this industry sector, which can be activated during periods of high energy generation or low demand. Consequently, the generated electrical energy can be efficiently utilized through DR applications in the industrial sector. In this context, the outcomes of the study can contribute in addressing one of the UN SDGs, specifically Goal number 07, which is focused on ensuring reliable and sustainable access to energy. Moreover, this study indicates that through DR techniques a significant demand flexibility can be attained from the cement industry, which could be leveraged alongside available resources, particularly in the context of variable renewable energy sources (VER).

Furthermore, as discussed in Chapter 1, despite the hydropower-dominated energy mix of the Ethiopian power grid, approximately 2% of its source is derived from diesel. Minimizing the energy demand during peak hours of the day could reduce the energy supply from this source. Hence, in addition to peak minimization, DR strategies could have grid emission reduction potential. To estimate the CO_2 emission reduction potential of the proposed model within the case study cement plants, a 0.533 CO_2/MWh emission factor of diesel power plant is taken, based on the IPCC guidelines, Chapter 2, stationary combustion (IPCC, 2006), and the

UNFCCC methodological tool (United Nations Framework Convention on Climate Change [UNFCCC], 2013). Consequently, the study found that 69, 76.5, and 42.6 tonnes of CO_2 emissions reduction per day have been achieved from case study cement plants 1, 2 and 3, respectively. These results highlight the potential for reducing CO_2 emissions from a power grid through the implementation of DR activities in the cement industry.

In this study industry surveys and data collection were started in 2019 and continued into 2020. These years were particularly challenging due to the COVID-19 pandemic and political instability in the country, which made surveying the industry and gathering reliable data difficult. This may be one of the limitations of the study, and future considerations could take these circumstances into account.The data obtained for 2020 was significantly better in quality and consistency compared to 2019, making it the reference year for analysis across all surveyed plants. Importantly, the energy performance indicators are evaluated on a per-ton-of-cement-produced basis, which helps normalize variations in production. Additionally, a sensitivity analysis was performed assuming a 100% capacity factor for the surveyed plants to assess how this assumption might affect the results compared to the actual 2020 data.

To assess the energy performance of the Ethiopian cement industry, monthly individual data from seven cement plants was used to determine their energy intensity. The Energy Intensity Index (EII) of each plant was then estimated using the BEST-cement tool. In this context, the impact of capacity factor does not significantly affect the results, since energy intensity measures the specific energy consumption per ton of cement produced. However, the energy demand flexibility assessment relies on aggregated data, which can be more sensitive to the capacity factors of individual plants. It would indeed be better to focus on months where plants operated at higher production levels. This issue is addressed in the proposed energy optimization model, which uses monthly data for each plant with capacity factors above 70% as input for evaluation.

5.3 Scenarios Analysis for the DR and WHRPP Potentials

The findings presented in Chapter 4, section 4.3.2 is based on the annual capacity factors (CFs) of 86%, 88% and 76% of their production capacity for Plant-1, Plant-2, and Plant-3, respectively. However, it is crucial to note that the potential for demand response in these plants could fluctuate with changes in cement production volume. Table 5.2 demonstrates the fluctuations in energy shifted and CO_2 emissions reduced during peak period by the optimal DR strategies under different capacity factor (CF) scenarios. When cement production in the

plants reaches maximum capacity (100% CF), the DR potential reduces. This occurs due to the fact that at maximum production capacity, the idle time of processing machines could be minimal, resulting in a limited DR potential to the power grid. This situation is depicted in Table 5.2, where the aggregate shifted energy consumption of the plants during peak hours reduced from 353.5 MWh (base case values) to 260.5 MWh (100% CFs) with the optimal DR strategy. Conversely, when cement production decreases relative to the base case values, the idle times of these machines are further extended. This is evident in Table 5.2, where the total energy shifted of the cement plants during peak hours increased from 353.5 MWh (base case values) to 438.7 MWh (with a 10% reduction of CFs from the base case values) with the proposed optimal DR strategy. Hence, the DR obtained from the cement plants can vary deepening on the daily production volume of cement.

Ethiopia currently employs a flat-rate electricity tariff, which maintains a uniform price throughout the day. This pricing structure is not conducive to adapting demand response (DR) strategies on the consumer side, as it does not incentivize users to shift their electricity usage based on time-of-day pricing signals. Therefore, in this study, the average Time-of-Use (TOU) electricity tariffs of selected East African countries were adopted and applied to the proposed model. This approach aims to provide policy-makers with insights into the potential cost-effectiveness of DR strategies for end-users. The selected countries were chosen based on two key criteria: their electricity grids are dominated by renewable energy sources, and they share a similar level of socio-economic development with Ethiopia. It is assumed that the average TOU price structure can be better to forecast the Ethiopian case than relaying on data from a single country. It is also possible to consider the specific cost of electricity generation (thermal unit price) of the Ethiopian electricity grid within the model. However, in this study, the primary focus was on assessing the impact of demand response strategies under a timely varying electricity price scheme like TOU tariffs. Nonetheless, future work can be extended to include a more detailed supply-side electricity generation cost analysis in the model.

Furthermore, it's important to highlight that the DR potential derived from the cement industry can be even more substantial, especially when onsite power generation is employed in a typical cement plant. In addition to waste heat recovery power plants, renewable energy power plants such as wind farm and solar power plants can be considered as an onsite power generation plant in cement industry. However, the LCOE of these options are much higher than the WHRPPs. According to (IRENA, 2019), the average LCOE for solar photovoltaic,

solar thermal and wind power plants in 2019 were about 0.12, 0.28, and 0.06 USD/kWh, respectively for sub-Saharan Africa. Similar study shows that the weighted average LOCE for wind power plant in Africa by 2019 was about 0.07 USD/kWh (Alemzero et al., 2021). However, as the availability of renewable energy sources are high in Ethiopia, by integrating wind farm and/or solar thermal power plants with WHRPP in the cement plant site, the onsite power generation potential could be enhanced, reducing more the dependency from the utility grid. Moreover, by implementing the feasible onsite electric power generation mechanism in the cement industry and integrating it with the proposed optimal operational DR model, it could potentially enhance the demand response capability of the sector to the power grid. This aspect could be explored further in future research endeavors.

Table 5.2: Variations of energy shifted and CO_2 emission reduced during peak hours by the optimal DR model at different capacity factors (CF) scenarios.

Case Study Plants	Reduced energy consumption and CO_2 emissions during peak hours					
	CF[a] (at 10% reduction from BC[b] value)		CF (base case values)		CF (at 100% production capacities)	
	Energy shifted (MWh)	CO_2 emission reduced (t)	Energy shifted (MWh)	CO_2 emission reduced (t)	Energy shifted (MWh)	CO_2 emission reduced (t)
Plant 1	165	88	130	69	123	65.6
Plant 2	171.4	91.4	143.5	76.5	98	52.2
Plant 3	102.3	54.5	80	42.6	39.5	21.1
Total	438.7	234	353.5	188.1	260.5	139

[a]: Capacity Factor, [b]: Base Case values

5.4 Policy Implication

Demand side energy management (DSM) strategies have been widely implemented worldwide to ensure grid stability and reduce carbon emissions in the energy sector. In the United States, power utilities have reported a potential peak demand savings of over 31 GW in 2019 through DR participation, with industrial customers accounting for 15 GW of this total and representing approximately 3.3% of the grid's total peak demand (Federal Energy Regulatory Commission, 2021). A case study conducted at a steel factory in Iran (Kholerdi & Ghasemi-Marzbali, 2021), indicates that interactive time-of-use (TOU)-DR strategies could lead to a 18.6% reduction in peak hour energy demand. Similarly, research in Nordic countries suggests that the overall potential for peak-shaving through demand-side response measures ranges between 12% to 23% of their total peak demand (Söder et al., 2018). Furthermore, the International Energy Agency (IEA), in its World Energy Outlook (2017) report, estimated that that approximately 185 GW of demand-side flexibility could be achieved cost-effectively by 2040 (IEA, 2017). This report also highlights that the global

theoretical potential for demand response exceeding 15% of the total electricity demand. Hence, these studies and international references validate the credibility of the findings of the current study to be used as a reference for future policy interventions.

The realization of DSM, particularly demand response potential requires appropriate price signals and regulatory frameworks that create incentives for participants. Retail tariff structures, such as time-of-use (TOU) or real-time pricing can offer the necessary price signals to consumers, enabling them, as well as aggregators and other demand-side resources to participate in wholesale markets for energy, capacity, and ancillary services, thereby fostering investment. In this study the average TOU price tariffs of the East African countries has been applied to show the viability of demand response (DR) within the Ethiopian power grid, focusing on the cement industry as a case study. The research findings proved that DR applications have the potential to reduce peak demand on the grid and decrease costs for users. The results highlight how DR applications can effectively reduce peak demand on the grid and lower costs for users. However, the current flat rate tariff scheme in Ethiopia cannot incentivize users to participate in DR activities. Thus, the country's energy policymakers should consider developing timely varying price structure like TOU to leverage the benefits of DR in the power system. Moreover, users' participation in DR program can enhance the integration of variable renewable energy resources (VER), improving flexibility and reliability in the electricity system. Furthermore, the successful adaptation of DR strategies requires the establishment of adequate infrastructure and tools to realize their benefits. These setups include information and communication technology (ICT), advanced metering infrastructure (AMI), surveillance systems and sensors, enabling bidirectional communication between the grid and end-users. Therefore, it is advisable for the Ethiopian power grid to formulate a comprehensive plan for deploying DR infrastructure while also fostering customer awareness and participation through well-designed pricing mechanisms. Thus, this research has the potential to inspire policymakers to gain valuable insights into demand response strategies aimed at ensuring the security of the electricity supply and mitigating climate change. It could also encourage the exploration of ways to implement demand-side energy management strategies alongside well-suited electricity pricing structures.

Overall, this doctoral study explores the adaptation of Demand Side Management (DSM) strategies in the industrial sector, including investigating the annual energy-saving potential and cost-effectiveness of various energy efficiency measures and technologies, assessing energy demand flexibility potential using the proposed model that integrates demand response (DR) strategies into the energy utilization and production plan of the industry sector, and

conducting the techno-economic analysis of onsite electricity generation particularly Waste Heat Recovery (WHR) power plants in the case of the cement industry. This study demonstrated that all of these DSM strategies can benefit both the electric utility and the industrial user. The significance of these strategies varies depending on the perspective whether from the electricity grid or the industrial users, such as the cement sector. From the grid's standpoint, the developed DR strategies and proposed onsite generation systems are particularly crucial for maintaining a balance between electricity supply and demand. On the other hand, for the cement industry, implementing energy-efficient technologies and practices holds the greatest value, as it helps reduce overall energy consumption, emissions, and operational costs.

Chapter 6: Conclusions and Recommendations

This PhD study proposes sustainable energy utilization practices in the context of the cement industries in Ethiopia. The overreaching aim is to alleviate the impact on the national power grid, simultaneously lowering their specific energy consumption, associated costs, and emissions. In this study, demand-side management (DSM) strategies, encompassing energy efficiency, demand response, and onsite power generation potentials, which play a crucial role in enhancing the sustainability and competitiveness of the industrial sector have been effectively investigated. The study proves that by implementing DSM initiatives, industrial facilities can optimize their energy consumption, reduce costs, and contribute to environmental conservation.

To address the first specific objective of the study, assessing the energy and environmental performances of the Ethiopian cement industry (RO1), the energy utilization and CO_2 emission performance of the cement plants in Ethiopia have been assessed and compared against best practices using a robust benchmarking tool (BEST-Cement). The findings indicate that Ethiopian cement plants demonstrate lower efficiency compared to established best practices, suggesting that approximately 36% of their energy demand could be saved through the implementation of energy efficiency measures and technologies. The assessed plants exhibited electrical energy intensities ranging from 111 to 171 kWh/tonne and fuel intensities from 3.03 to 4.83 GJ/tonne of cement, with respective average values of 132 kWh/tonne and 3.55 GJ/tonne in 2020. The annual average CO2 emission intensity of the plants is approximately 337 kg CO2/tonne of cement, primarily due to fuel combustion, with an average clinker-to-cement ratio of 0.8.

Then, this study explores potential energy savings and emission reduction strategies in the cement industry (RO2). Twenty-eight potential cement-specific energy efficiency measures (EEMs) have been identified and examined using a bottom-up energy conservation supply curves (ECSC) model. Accordingly, the electricity saving potential of the cost-effective measures included in the EECSC amounts to 98.7 GWh, representing 11.5% of the plants' annual electricity demand. The total electricity saving potential of the 17 measures is 284 GWh, covering 33% of plants' annual electrical energy consumption. The majority of the energy efficiency measures incorporated in the FCSC model are cost-effective, with a fuel-saving potential of 2.7 PJ, which represents 12.5% of the plants' annual fuel consumption. The overall fuel-saving potential of the 11 measures included in the FCSC model is estimated

at 3.1 PJ. These findings highlight that energy-efficient technologies and measures can significantly reduce the specific energy consumption of cement production in Ethiopian cement plants. Additionally, the cost-effective fuel-saving measures could lead to a CO_2 emission reduction of 254 kt, accounting for 5% of the plants' total emissions in 2020. Nevertheless, the emission reduction potential from electricity savings is negligible.

The potential of energy demand flexibility in the cement industry has been assessed, aimed at addressing the power grid's challenges in balancing supply and demand during peak periods. Subsequently, demand flexibility energy optimization model suitable for conventional power grids has been developed (RO3). The study utilizes data from the Ethiopian cement industries and the national power utility. The analysis reveals that the cement milling and raw milling units of the cement plants exhibit the highest demand flexibility potential, with daily values of 275 MWh and 179 MWh, encompassing both load curtailment and load shifting. These figures represent 15.5% and 10% of the total daily energy usage of the examined cement plants, respectively. Additionally, the coal milling and packing & loading units demonstrate demand flexibility potentials of 24 MWh and 18 MWh per day, respectively. Overall, the total demand flexibility potential of the primary machines of the case study plants is estimated to be 495 MWh per day, constituting around 28% of their daily electricity demand. Since demand response strategies help mitigate peak loads by shifting or reducing energy use, these findings could contribute to addressing grid instability issues linked to peak demand. However, a comprehensive assessment of technical and economic feasibility is necessary, emphasizing the integration of energy consumption optimization with detailed production planning through an appropriate modeling framework.

Hence, a MINLP model is developed to address the third specific objective of the study, evaluating the optimal viability of demand response for industrial users. The proposed model successfully demonstrates an optimal operational schedule for each case study plant, leading to a reduction in both the daily energy expenses of the factory and the peak electricity demand, as well as emissions from the national power grid. By implementing this model, the peak-period loads of the case study plants are reduced by approximately 75% on average, while the total energy used during peak hours decreases by around 70%. The reduced peak loads are shifted to off-peak and shoulder periods, thereby optimizing energy use throughout the day. Additionally, the model results in a daily CO_2 emission reduction of 188 tonnes across the case study plants. Moreover, under a Time-of-Use (TOU) pricing scheme, the daily electricity costs in these plants decrease by an average of 14% with the revised schedule. The results

confirm that the proposed model can effectively lower energy costs in cement plants through demand response strategies. In addition, the study explores additional scenarios, such as varying the capacity factors of the plants and considering on-site power generation from solar and waste heat recovery systems, which could further enhance demand response potential within the cement industry.

Finally, as significant energy is wasted as exhausted heat in cement manufacturing, the viability of waste heat recovery power generation in the case of the Ethiopian cement industry is investigated in this study, aiming for potential energy gains, cost, and emission reductions (RO4). The life cycle cost (LCC), levelized cost of energy (LCOE), and net present values (NPV) of the three waste heat recovery technology options for electricity generation have been evaluated. Accordingly, for steam RC-based WHRPP, the LCOE and NPV are about 0.04 USD/kWh, and 0.35 million USD, respectively. While for ORC-based WHRPP, about 0.06 USD/kWh, and -3.2 million USD are obtained for LCOE, and NPV, respectively. For the third option, Kalina RC-based WHRPP, 0.06 USD7kWh, and -4.7 million USD are obtained for LCOE, and NPV, respectively. The findings prove that SRC-based WHRPP emerges as both technically and economically viable for the cement plant studied in Ethiopia, with power generation capacity of 8.9 MW, covering 18% of the case study cement plant annual electricity demand, reducing the dependency of electricity consumption from the national grid.

In conclusion, the study's findings prove that the cement industry is a strong candidate for adopting demand-side management (DSM) strategies. A comparison of the main results with related studies and international benchmarks confirms their validity. To ensure the robustness of the findings, a sensitivity analysis has been performed, accounting for potential fluctuations in key influencing parameters. Therefore, this thesis serves as a valuable reference for energy policymakers and industry stakeholders in formulating effective strategies and policies for DSM adoption. The approaches and methods applied in this study can also be used by similar energy-intensive industries in other countries to develop similar DSM framework. Moreover, the study highlights the consideration of renewable energy resources, such as wind farms and solar power plants to integrate with the WHRPP in the cement plant sites, which could boost onsite energy generation potential, leading to enhanced energy efficiency and increased DR capabilities within the cement sector. However, the detailed development of this idea is left for future study.

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Appendices

Appendix A: Supplementary data used for the investigation of energy saving and climate mitigation potentials in cement production

Table A1: Raw materials and fuel/coal consumption (in tonne) from the surveyed cement plants (2020 Production year)

Plants	Raw Materials (RM)			Total crushed RM	Additives			Total Crushed Additives	Raw Meal	Coal/Fuel Consumption				
	LM[a]	Clay	Sand /Bazalt		Gypsum	Pumice	Rhyhiote /LM filler			SA[b] coal (ton)	Local[c] coal (ton)	Petcoke (ton)	HFO (ton)	carbon Bl.(ton)
Plant 1	2,378,420	225,415	131,955	2,567,008	150,736	321,951	-	466,226	2,671,545	154,823	154,022	0.00	0	0
Plant 2	2,190,399	345,790	232,052	2,677,421	166,493	163,131	-	310,470	2,677,421	111,496	188,066	5,097	5,097	0
Plant 3	767,733	118,243	80,331	938,433	44,972	159,193	-	198,991	938,433	63,128	61,031	0.00	462	0
Plant 4	1,034,544	149,954	111,177	1,277,358	57,338	112,497	104,813	268,907	1,277,358	112265	8885	0.00	0	0
Plant 5	430,660	66,329	45,061	526,414	20,273	85,791		103,732	526,414	32,375	39,521	0.00	0	0
Plant 6	-	-	-	384,875	-	-	-	197,389	384,875	49530	0	0.00	0	0
Plant 7	122,953	13,816	-	124,614	400	19,955	-	15,367	137,838	0	12652	8,068	0	389

[a] Lime stone, [b] South African, [c] local coal means Ethiopian coal

Table A2: Annual production and energy consumption of the surveyed plants in 2020

Plants	Raw meal Production (Mt)	Clinker Production (Mt)	Cement Production (Mt)	EE[a] consumption (GWh)	Fuel consumption (GJ)	Clinker – cement ratio	Utilization Capacity (%)
Plant 1	2.672	1.64	2.138	237	6,464,280	0.76	86%
Plant 2	2.677	1.71	2.032	245	6,330,333	0.84	88%
Plant 3	0.938	0.60	0.796	136	2,599,435	0.75	36%
Plant 4	1.277	0.83	0.919	120	2,967,000	0.89	76%
Plant 5	0.526	0.32	0.406	68	1,476,241	0.79	29%
Plant 6	0.385	0.25	0.336	38	1,243,402	0.73	44%
Plant 7	0.138	0.08	0.103	12	498,313	0.81	15%

[a] Electrical Energy

Table A3: Total CO_2 emissions by the surveyed plants in 2020 (Thakuri et al., 2021) (IPCC, 2006) (United Nations Framework Convention on Climate Change [UNFCCC], 2013)

Clinker (Mt)	Electricity (GWh)	fuel (GJ)	EF_{clc} (Mt [b] CO_2/Mt cl)[c]	EF_{EE} (t[a] CO_2/GWh)[d]	EF_{fuel} (t[a] CO_2/GJ)[e]	CO_2 emission by process (Mt)	CO_2 emission by Electricity (Mt)	CO_2 emission by fuel use (Mt)	Total CO_2 Emission (Mt)
1.64	237	6,464,280	0.52	6.00	0.09	0.85	0.0014	0.61	1.46
1.71	245	6,330,333	0.52	6.00	0.09	0.89	0.0015	0.60	1.49
0.60	136	2,599,435	0.52	6.00	0.09	0.31	0.0008	0.25	0.56
0.83	120	2,967,000	0.52	6.00	0.09	0.43	0.0007	0.28	0.71
0.32	68	1,476,241	0.52	6.00	0.09	0.17	0.0004	0.14	0.31
0.25	38	1,243,402	0.52	6.00	0.09	0.13	0.0002	0.12	0.25
0.08	12	498,313	0.52	6.00	0.09	0.04	0.0001	0.05	0.09
Total									**4.86**

[a] t: tonne, [b]Mt: million tonne

[c] emission correction factor for clinker including CKD correction (EF_{clc}) is about 0.52 Mt CO_2/Mt clinker as per IPCC guideline.

[d] emission factor for electricity (EF_{EE}) used here is 6 t CO_2/GWh which is equivalent to 0.006 kg CO_2/ kWh as obtained from UNFCCC methodological tool

[e] emission factor for fuel combustion (EF_{fuel}) used here is 0.09 t CO_2/GJ which is equivalent to 94.6 kg CO_2 /GJ as obtained from IPCC Guidelines for National Greenhouse Gas Inventories.

Appendix B: Data sources used for DR potential assessment:

Table B1: Mass production and electrical energy consumption daily limit by the main processing machines of the case study cement plants(obtained from industry survey and (Mossie et al., 2023))

No.	Main loads/machines	Output	Mass of production (Kt/yr)			Daily total energy consumption (MWh) of each plant (for a sample date)		
			Plant 1	Plant 2	Plant 3	Plant 1 (Jan 18, 2020)	Plant 2 (Jan 2020 (average))	Plant 3 (Jan 2020 (average))
1	RM	raw meal	2672	2677	1277	220	92.7	102.6
2	CM	cement	2138	2032	919	340	232.5	88
3	CG	coal	309	310	121	24	15.4	12
4	Crusher	crushed limestone	2672	2677	1277	8	4	5
5	Packaging	cement	2138	2032	919	17	8	3
6	Kiln	clinker	1640	1710	830	232.8	228	129.6
7	Lighting	cement	2138	2032	919	7.2	4.8	3.6
Total						849	585.4	343.8

RM –Raw Mills, CM – Cement Mills, CG – Coal Mills,

The utilization factors of the three case study cement plants are: 86% for plant – 1, 88% for plant – 2 and 76% for plant 3 (Mossie et al., 2023)

Table B2: Daily energy consumption and cost of energy use by the case study cement plants

	Total energy consumption (MWh) for a day							Cost of energy use per day (USD)					
	Plant 1		Plant 2		Plant 3		TOU price	Plant 1		Plant 2		Plant 3	
	Initial State	Proposed Model	Initial State	Proposed Model	Initial State	Proposed Model	USD/MWh	Initial State	Proposed Model	Initial State	Proposed Model	Initial State	Proposed Model
Peak	208	78.5	192.3	48.8	108.4	28.5	90	18720	7065	17307	4392	9756	2565
Shoulder	446.9	437.4	314.7	231	176.8	142.7	70	31283	30618	22029	16170	12376	9989
Off-peak	194.2	333.2	78.4	305.6	58.6	172.7	50	9710	16660	3920	15280	2930	8635
Total	849	849.1	585.4	585.4	343.8	343.9		59713	54343	43256	35842	25062	21189

The peak, shoulder, and off-peak periods are taken from the Ethiopian hourly power demand curve (obtained from Ethiopian Electric Power, Load Dispatch Center)

The TOU price rates are the average TOU tariff structures of the East African countries (EPRA, 2022) (*ERA*, 2021)

Paper 1

Paper 2

Paper 3