ENERGY CONSERVATION AND EMISSION REDUCTION POTENTIAL THROUGH SOLAR ENERGY APPLICATIONS IN CEMENT INDUSTRY

A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

by

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SEPTEMBER 2024

ACKNOWLEDGEMENTS

I would like to express my heartiest gratitude to my research supervisors, mentors, and guides Dr. Anil Kumar and Dr. Samsher for their supervision, advice and continuous guidance from the conception of this research as well as for imparting extraordinary experiences throughout the work. Their advice on both research as well as on my career has been priceless. If I would stand proud of my achievements, they are the main creditor. It is my privilege to be under their tutelage. Perseverance, exuberance, and positive approaches are just some of the traits they have imprinted on my personality. I thankfully acknowledge him for their vital contribution, which made them the backbone of this research and hence this Thesis.

I extend my heartfelt appreciation to Prof. Prateek Sharma, Hon'ble Vice Chancellor of Delhi Technological University, Delhi (India) for providing me with the opportunity to conduct this research at this esteemed institution. I am also thankful to Atul Kumar Agarwal, Chairperson, Departmental Research Committee, and other committee members for their support and guidance.

I am indebted to my beloved parents, Mr. Gouranga Charan Sahoo and Mrs. Sailabala Sahoo, whose blessings and unwavering support have been the cornerstone of my achievements. I am also grateful to my wife, Mrs. Sarita Sahoo, daughter Nayonika Sahoo and son Naitik Sahoo for their unwavering support and patience throughout my Ph.D. journey.

I would like to special thanks to Dr. Anil Kumar Sethi and Dr. Manohar Singh for their invaluable support during challenging times and also, express my gratitude to all those who have contributed to the successful completion of this thesis. Though I cannot mention each individual personally, their support has been invaluable.

Finally, I offer my thanks to the Almighty for granting me the patience and strength to reach this significant milestone in my life.

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CANDIDATE’S DECLARATION

I Niranjan Sahoo hereby certify that the work which is being presented in the thesis entitled “**Energy Conservation and Emission Reduction Potential Through Solar Energy Applications in Cement Industry**” in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Mechanical Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from July 2019 to April 2024 under the supervision of Dr. Anil Kumar and Dr. Samsher.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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Energy Conservation and Emission Reduction Potential Through Solar Energy Applications in Cement Industry

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ABSTRACT

Cement is one of the most versatile construction materials used in the world. World cement consumption increased from 4.8 billion tons to 6 billion tons from 2016 to 2022. Cement production utilizes a considerable amount of fossil fuels to fulfill its thermal energy requirements. Coal, Petro coke, natural gas, and biomass are the most commonly used fossil fuels. Moreover, the combustion of fossil fuels releases many toxic gasses into the atmosphere. As a result, reducing fossil fuel usage is critical while maintaining the cement sector's thermal energy requirements. One best approach to minimize greenhouse gas emissions is to use fewer fossil fuels. This may be done by either increasing system efficiency to use less fossil fuel or by switching to renewable energy sources like solar energy in place of fossil fuel. Enhancing system efficiency is undoubtedly a good strategy, but only for a short period. However, the long-term benefits of solar energy implementation in the cement sector are significant.

This study describes the potential of solar thermal calciner technology and consequent carbon mitigation for Indian cement industries. Approach used to provide solar energy involves the installation of a solar tower system with a solar reactor atop the solar tower or preheater tower in a conventional cement plant. For potential estimation, locations of the clusters of cement plants with their actual annual cement production have been identified. Based on the annual actual cement production, the yearly process heating demand for the calcination process for each cement plant is estimated. The annual thermal energy savings by the use of solar calciner reactors was found to be 771.35 PJ. When all of the calciner's required thermal energy is replaced by solar energy, a maximum of 21% of the total CO_2 emission may be prevented. The usage of concentrated solar energy can prevent an estimated 45.193 MT of CO_2 emissions.

Furthermore, A case study was done on a conventional cement plant that is situated at a location with a DNI value of 438 (W/m^2). Analysis considered thermal energy substitution ranging from 100% to 50%. Solar power output of the reactor was 793 MW after considering the 45% heat loss in the reactor. The number of heliostats required for generating 793 MW solar reactor power was 15066 with a total required land surface of 1130 ha. Depending on the thermal losses i.e., 15%, 30%, and 45%, the net conversion efficiency was 44, 56, and 69, respectively. Implementing concentrated solar thermal (CST) in the calcination process of the selected conventional cement plant could save 419 thousand tons of CO_2 annually. Economic analysis suggests that approach is useful when there is a minimum thermal loss in the solar reactor. Payback time (PBT) and internal rate of return (IRR) for the design model were 10.4 years and 5.4% when there were 45% thermal losses in the solar reactor. Major challenges are regarding the conversion of laboratory equipment to industrial size, working in high-temperature environments, raw material transportation systems, and thermal storage systems.

The overall research work has undergone extensive analysis to produce responsible, system-effective results that are nourished by a detailed discussion of the results and conclusions, as well as future recommendations that may enlighten the researchers and inspire them to pursue additional potential developments in this field for the benefit of society, the environment, and the ecologically sustainable growth of peoples.

Keywords: Solar energy; Cement plant; Calcination reactor; Cement industry; Carbon emission reduction; Solar calcination; Solar cement plant

List of Publications

International Journal (04)

1. **Sahoo, N**., Kumar, A. & Samsher (2023). Design of solar cement plant for supplying thermal energy in cement production. Journal of Cleaner Production, 426, 139151. https://doi.org/10.1016/j.jclepro.2023.139151. **SCI Impact Factor: 11.1**
2. **Sahoo, N**., Kumar, A. & Samsher (2023). Potential of solar thermal calciner technology for cement production in India and consequent carbon mitigation. Process Safety and Environmental Protection, 179, 667-676. https://doi.org/10.1016/j.psep.2023.09.041. **SCI Impact Factor: 7.8**
3. **Sahoo, N**., Kumar, A., & Samsher (2022). Review on energy conservation and emission reduction approaches for cement industry. Environmental Development, 44, 100767. https://doi.org/10.1016/j.envdev.2022.100767. **SCI Impact Factor: 5.4**
4. **Sahoo, N**., & Kumar, A. (2023). Potential assessment of solar industrial process heating and CO_2 emission reduction for Indian cement industry. Solar Compass, 8, 100064. https://doi.org/10.1016/j.solcom.2023.100064. **SCOPUS**

International Conference (03)

1. **Sahoo, N**., Kumar, A., & Samsher. (2021, October). Solar Industrial Process Heating Prospects in Indian Cement Industries. In International Conference on Mechanical and Energy Technologies (pp. 367-374). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-1618-2_36
2. **Sahoo, N**., Kumar, A., & Samsher. (2020, October). A Preliminary Assessment of Solar Industrial Process Heating for Cement Industry. In International Conference on Energy, Materials Sciences & Mechanical Engineering (pp. 171-177). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-16-2794-1_15
3. **Sahoo, N**., & Kumar, A. (2020, July). Analyzing the Barriers of Green Construction Using Interpretive Structural Modeling. In International Conference on Recent Advancements in Mechanical Engineering (pp. 1119-1128). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-15-9678-0_93

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NOMENCLATURE

Latin Symbols

Atm_{ab} = Absorption capacity of the atmosphere

$C_{p,rm}$= Specific heat of raw material, J/kg K

$C_{p,Ta/Kg}$= Specific heat of Tertiary air/ Kiln gas, J/kg K

C_{co_2} = CO_2 emission factor for fossil fuel

Cos_{ef} = Plant's site cosine effect

H_{av} = Availability of heliostats

ha = Hectare

LHV= Lower heating value, kJ/kg

$\dot{m}$ = Mass flow rate in kg/s

$\dot{m}_{Ta/Kg}$= Mass flow rate of Tertiary air/ Kiln gas, kg/s

$\dot{m}_{rm}$= Raw material mass flow rate, kg/s

$\dot{Q}_{rxn}$ = Energy flux required for raw material calcination, W

$\dot{Q}_{solar}$ = Energy flux needed for the process, W

$\dot{Q}_{l}$ = Energy flux losses at the reactor, W

$\dot{Q}_{hrm}$ = Rate of energy required to heat raw material from the inlet to the reaction temperature, W

$\dot{Q}_{SR}$= Solar reactor power output, W

$\dot{Q}_{SR,th}$= Solar calciner thermal energy input rate, W

$\dot{Q}_{Ta}$= Tertiary air heat input rate, W

$\dot{Q}_{Kg}$= Kiln gas heat input rate, W

Rd = Dust discharge rate from preheater tower

sh = Factor for compensating shadowing and blocking in heliostats

SP_{reac} = Spilt solar radiation around the reactor

$T_{in,Ta/Kg}$= Inlet temperature of tertiary air/ kiln gas, ℃

$T_{out.gas}$= Common temperature of exit gas, ℃

T_{Calcin}= Calcination temperature, ℃

$T_{in,rm}$= Raw material inlet temperature, ℃

Greek Symbols

α_{SR} = Solar receiver absorptivity

ρ_{mr} = Reflectivity of mirrors

η_{th}= Solar calciner thermal efficiency, %

η_{SF} = Solar field efficiency, %

$\%Hum$= Content of humidity in raw material supplied to preheater tower

$\%CaO_{rm}$= % of CaO in raw material

$\%Lm_{rm}$= % of limestone in raw material

ΔH_{rxn}^{calc}= Heat of reaction during calcite calcination

Subscripts

$_{ab}$ = Absorption

$_{av}$ = Availability

$_{co_2}$ = Carbon dioxide

$_{Calcin}$= Calcination

$_{ef}$ = Effect

$\dot{}_{hrm}$ = Heat raw material

$_{in,rm}$= Inlet, raw material

$_{in,Ta/Kg}$= Inlet, tertiary air/ kiln gas

$\dot{}_{Kg}$= Kiln gas

$_{l}$ = Losses

$_{mr}$ = Mirror

$_{out.gas}$= Exit gas

$_{p,rm}$= Pressure, raw material

$_{p,Ta/Kg}$= Pressure, Tertiary air/ Kiln gas

$\dot{}_{rm}$= Raw material

$\dot{}_{rxn}$ = Raw material calcination

$_{reac}$ = Reactor

$_{rm}$= Raw material

$\dot{}_{SR}$= Solar reactor

$\dot{}_{SR,th}$= Solar reactor, thermal

$\dot{}_{solar}$ = Solar

$_{SR}$ = Solar reactor

$_{SF}$ = Solar field

$\dot{}_{Ta/Kg}$= Tertiary air/ Kiln gas

$\dot{}_{Ta}$= Tertiary air

$_{th}$= Thermal

Superscripts

^{calc}= Calcite

List of Abbreviations

ATER = Annual thermal energy requirement

AACP= Actual annual cement production

LS= Land surface (ha)

MS=Mirror surface (ha)

NH= Number of Heliostat

SIPHF = Solar incident power on the heliostat field (MW)

SPSR=Solar power out from the solar reactor (MW)

STER = Specific Thermal Energy Requirement (GJ/per tonne)

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Cement is one of the most versatile construction materials used in the world. World cement production capacity was 4400 million tons during 2021, produced by 170 countries across the globe (Fig.1.1). In 2015 the world cement production slightly decreased due to a significant decline in China's cement production. Production of cement again showed a good increase in 2016. From 2010 to 2016 production has accelerated around 890 million tons and further from 2017 to 2021 the acceleration is very slow and near about 300 million tons.

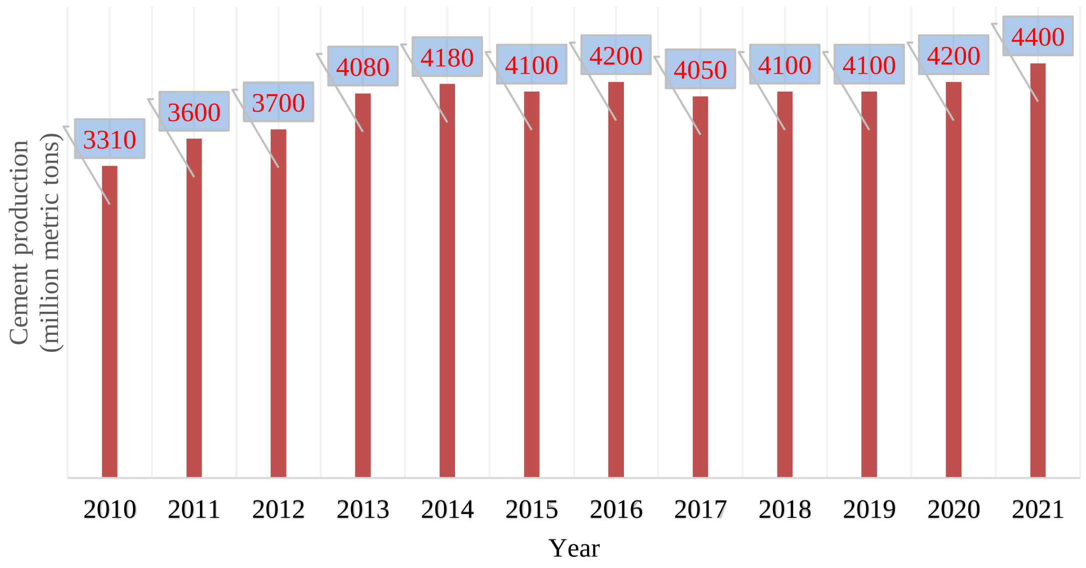


Fig.1.1 World cement production from 2010-2021

(Source: statista@2022, https://www.statista.com/statistics/1087115/global-cement-production-volume/)

Over half of the world's cement is currently produced by China, which accounts for approximately 2500 million tonnes and India is the second largest producer of cement with a total production of 330 million tonnes, followed by Vietnam. Cement production is highly unequal, with the top ten countries accounting for approximately 70% of global cement consumption. Mandal and Madheswaran (2010), documented that the cement production of India was 2.95 million tonnes in the year 1950–1951 and it increased to 330 million tonnes in 2020–2021. Fig. 1.2 shows the top cement production countries around the world in 2021.

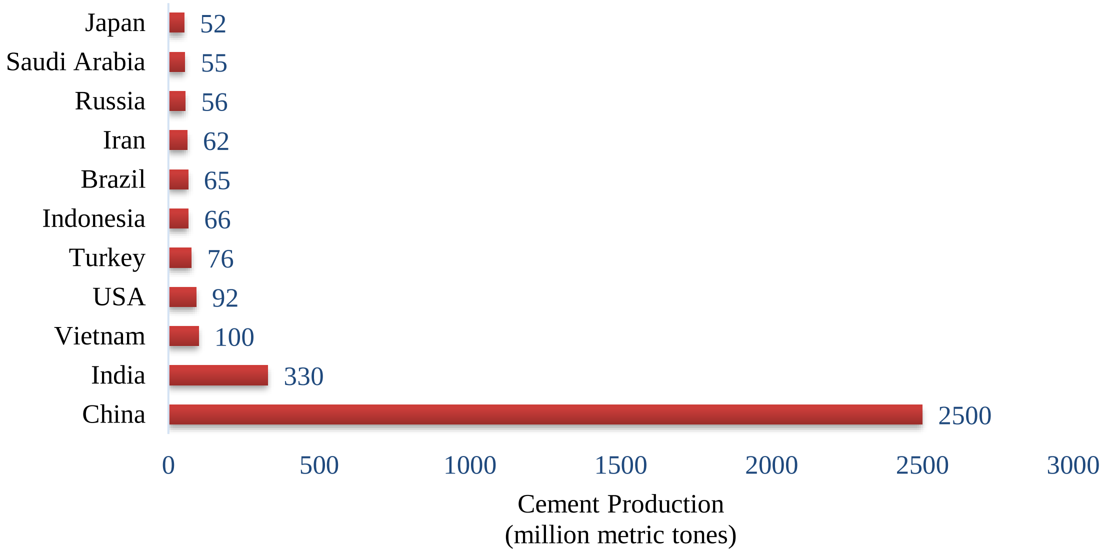


Fig.1.2 Top cement producers in 2021

(Source: Statista @2022, https://www.statista.com/statistics/267364/world-cement-production-by-country/)

In 2011, the world cement consumption was 3.59 billion tons and it increased to 3.75 billion tons in 2012 and the growth rate was estimated to be 4.3%. There was a constant growth in cement consumption from 2013 to 2015 globally. Moreover, world cement consumption is expected to increase from 4.8 billion tons to 6 billion tons from 2016 to 2022. Growth was accomplished due to the demand among developing economies in

Asia. On 11th March 2020, the World Health Organization announced the COVID-19 outbreak as a pandemic. This announcement forced the government of most countries to impose unprecedented lockdowns and as a result, the economic activities were drastically affected, particularly in the second and third quarters of the year. Construction activity was hit hard at first, and the cement industry came to a standstill entirely in certain areas.

There was a significant reduction in cement demand during the early months of the pandemic, which imposed much pressure on world economics. Global cement consumption declined 0.23 % in 2020 compared to 2019, to 4143.71 million tonnes, but per capita demand remained stable at 540 kg. In 2020, China achieved a YoY rise of 2.17 %, with volumes reaching 2377.68Mt. Outside of China, worldwide demand declined by 3.29 %. However, there was significant regional variance. Indian Subcontinent (-11.91%), South Asia (-8.26%), and North Africa (-8.04%) were the most impacted regions, with the biggest decreases, as the pandemic and subsequent lockdowns hindered building activity.

China consumed more than 59% of the world's cement and India consumed another 7% of world's cement. Other countries that are major consumers include Brazil, Russia, and Spain. Fig. 1.3 shows the top cement-consuming countries in 2017. India and China dominate the world's cement consumption and it is expected that these two countries consume two-thirds of the world's cement. Rapid urbanization is the main factor for cement consumption in China and India. Despite being the world's largest cement producers, much of their production did not export as it was consumed domestically.

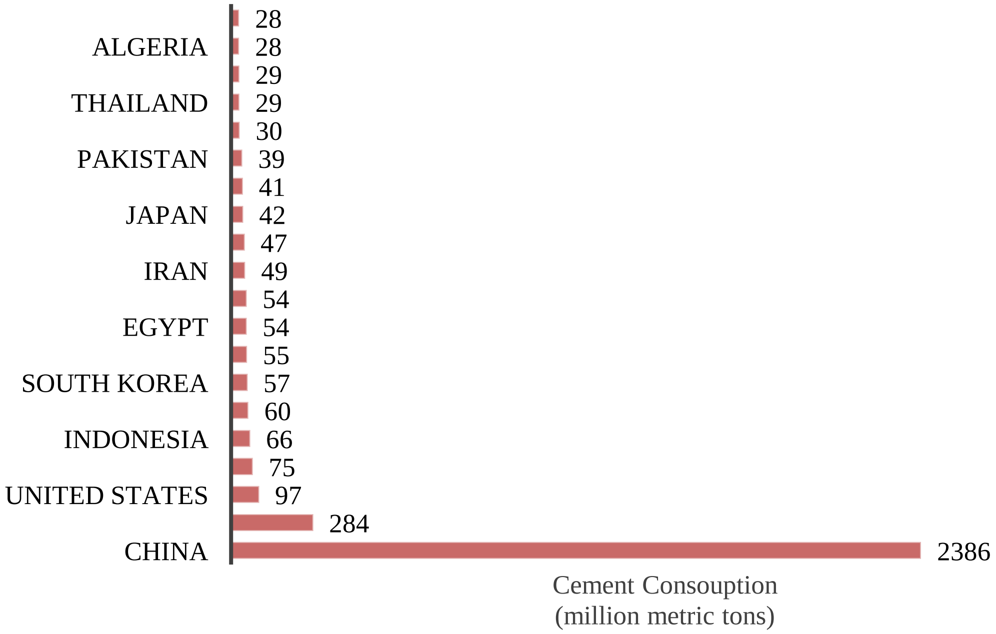


Fig.1.3 Top cement consumers in 2017

(Source: International Cement Review, November-2018)

Energy is one of the basic primary requirements for the existence and growth of any industrial sector. It is well established that a country's economic growth is directly related to the energy consumption by its industrial sectors. This sector consumes 54% of the world's total delivered energy which is very high in comparison with any other sectors. According to International Energy Outlook 2016 (IEO 2016), the energy consumption of all the industrial sectors around the world is increasing by an average of 1.2% per year. The world's industrial sector energy consumption is expected to reach a value of 309 quadrillion British thermal units in 2040. Cement industry is one of the energy-intensive industries which utilizes a sizable amount of energy. Cement industries in Malaysia consume about 12% of the country's total energy, while this value is 15% in Iran (Avami and Sattari, 2007).

Production of cement needs a tremendous amount of energy and it is in the form of thermal and electrical respectively. Thermal energy is utilized for heating various processes such as blending and homogenization, precalcination, pyro processing, etc., whereas electricity is used to operate air compressors, coolers, grinding units, lighting systems, etc. The thermal and electrical energy required for the different processes of cement production is shown in Fig.1.4.

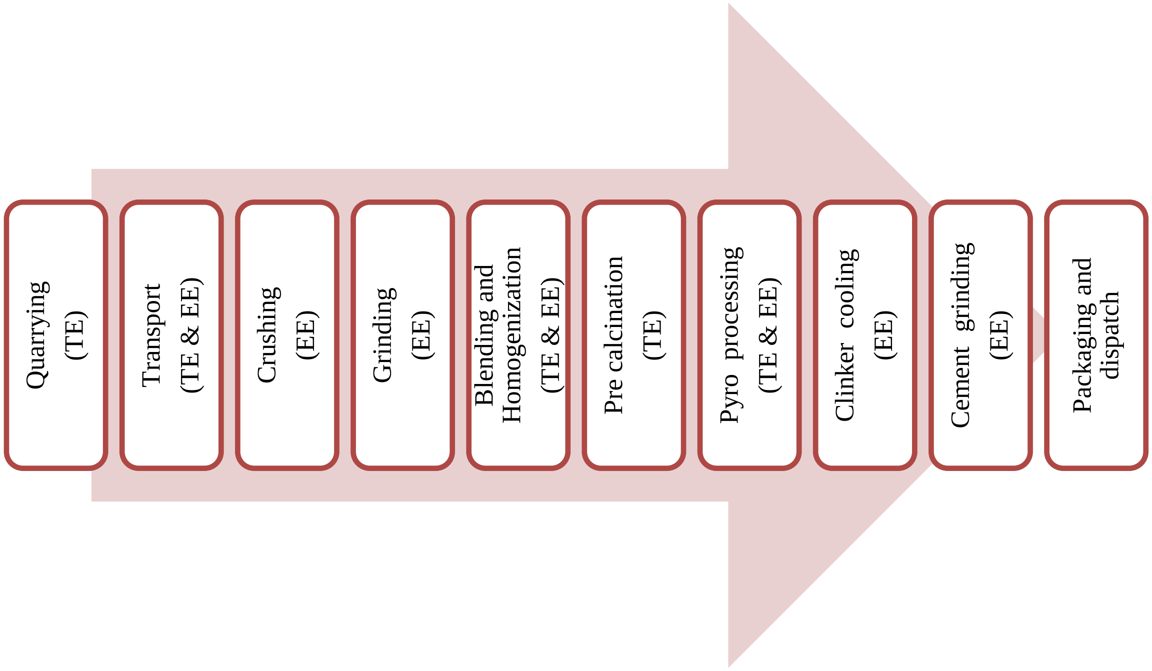


Fig.1.4 Outline of cement manufacturing processes with nature of energy requirement (Energyefficiencyasia, 2020)

Generally, four types of processes are used for cement manufacturing (Van Oss, and Padovani, 2002). A classification of the four processes can be described as follows:

Dry process: In this process, a dry raw meal is used as raw material fed to a preheater tower before entering into the rotary kiln.

Semi-dry process: In this process, the dry raw meal is shaped into pellets first and then these pellets are heated in a preheater tower before entering into the rotary kiln.

Semi-wet process: In this process, water is first removed from the raw slurry and then pellets are formed from the raw slurry, which is fed to the preheater for (dry) raw meal production before entering into the preheater/ precalciner kiln.

Wet process: The wet process of cement manufacturing uses the raw slurry as raw material and a long rotary kiln. The raw slurry is directly fed to the rotary kiln. Drying/preheating the raw material occurs within the rotary kiln (Cembureau, 1997).

Out of these four methods of cement manufacturing, two methods i.e., the dry process and the wet process, are mostly used. Dry cement manufacturing process uses a dry raw meal that contains less than 20% moisture by mass. However, the wet process uses slurry prepared by adding water to the raw meal. Nowadays, most of the cement industries prefer the dry process rather than the wet process because drying the moisture from the raw meal consumes high thermal energy. The basic process remains the same for cement manufacturing whether it is used dry/wet.

1.2 CEMENT MANUFACTURING PROCESSES

The production of cement needed a series of processes. These include (i) Quarrying and crushing of limestone (ii) Addition of additives (iii) Raw meal preparation (iv) Blending and storing (v) Preheating and pre calcining (vi) clink erization (vii) Clinker cooling and final grinding and (viii) packaging and dispatch. The next paragraphs provide a detailed description of the processes that are involved in quarrying to packing.

1.2.1 Quarrying and crushing of limestone

The primary raw material used for the cement production is limestone. Other raw materials used are silica, alumina and iron. Limestone contains 75-90% calcium carbonate ($CaCO_3$) and few percentages of magnesium carbonate ($MgCO_3$) and impurities. Strength of the cement is mainly due to lime and silica. Grey color appearance of the cement is due to the presence of iron and reduces the reaction temperature. The raw materials are extracted through drilling and blasting, generally known as quarrying operations. After extraction, the raw materials are crushed to the required size with the help of crushers. For obtaining 25mm size of the limestone two crushers are used i.e., a primary and a secondary. A tertiary crusher may be used to further reduce limestone sizes. After that, the crushed limestones are shifted to the cement plant with the help of bulldozers and trucks (Madlool et al., 2011; Madlool et al., 2012; Ahamed et al., 2012).

1.2.2 Addition of additives

To obtain the required raw mill some additives are added to the limestone. Most commonly used additives are iron, bauxite, silica and quartzite, etc. It can be done by storing the raw materials in silos or hoppers and then shifting them with conveyor belts help (ACC, 2015).

1.2.3 Raw meal preparation

For the dry process, the raw meal is prepared by drying and grinding the raw materials. Drying is done by using the excess heat from the rotary kiln system and for the grinding operation either a ball mill or a vertical roller mill (VRM) is used. There are generally different sizes of balls within the ball mills and the position of each ball is fixed by using a classifying liner. The bigger balls are used for impact grinding while the smaller balls are used for attrition grinding. A VRM adopts compression principle on the raw material for grinding. The selection between a ball mill and VRM is determined by many criteria which include percentage of moisture present and hardness of the raw material, the capacity, thermal and electrical energy consumption of the plant and economic viability, etc.

1.2.4 Blending and storing silo

The composition of the raw material fed into the rotary kiln system has a significant impact on both the effectiveness of the kiln and the quality of the clinker that comes out of it. The components in the raw material should be properly blended and homogenized to prevent variability. For proper blending and homogenization of the raw components, continuous blending silos are utilized.

1.2.5 Preheating and pre-calcining of raw material

As the name suggests pre-heating means the heating of raw materials before they enter into the rotary kiln system. This process is done only for the dry process of cement manufacturing. The preheating is done in a tower known as a preheater tower which is made of several vertical cyclones. Pre-heating the raw material is accomplished with the help of hot gasses that are released from the kiln to reduce energy consumption and improve the environmental friendliness of the cement-making process. To heat the raw material to a temperature of around 1000–1200°C, hot air is pulled into the cyclone from the opposite direction of the material flow (Rahman et al., 2015). The modern cement manufacturing plant contains a combustion chamber that is internal to the preheater tower. This is commonly known as pre-calciner.

1.2.6 Kiln phase

The kiln system is the most important part of a cement manufacturing unit. It consists of a large inclined steel tube that rotates between 0.5 and 4.5 revolutions every minute. The diameter of this rotating kiln ranges from 3 to 9 meters, and its length varies from 50 to 200 meters respectively. The slope of the rotary kiln ranges between 2.5 and 4.5% to the horizontal. For an efficient heat transfer, the raw material enters from the higher side of the kiln and moves slowly to the lower side. The firing is done at the lower end of the rotating kiln with the use of fossil fuels (coal) (Ravindran et al., 2016; Engin, 1997). Different types of zones in rotating kilns with temperature variations are shown in Fig. 1.5. Rotary kilns can be designed for handling a broad range of capacities, from small, batch-scale units processing anywhere from 50 to 200 lb/hr, to commercial-scale units processing material in the range of 200 lb/hr to 20 TPH. Large commodity kilns such as those used in the cement industry can process up to 50 TPH, but these size kilns are less common for many of the lower-capacity processes in use today. Residence time, also known as retention time, is the amount of time in which the material is processed in the kiln. As with temperature, the residence time is determined solely by the requirements of the intended reaction.

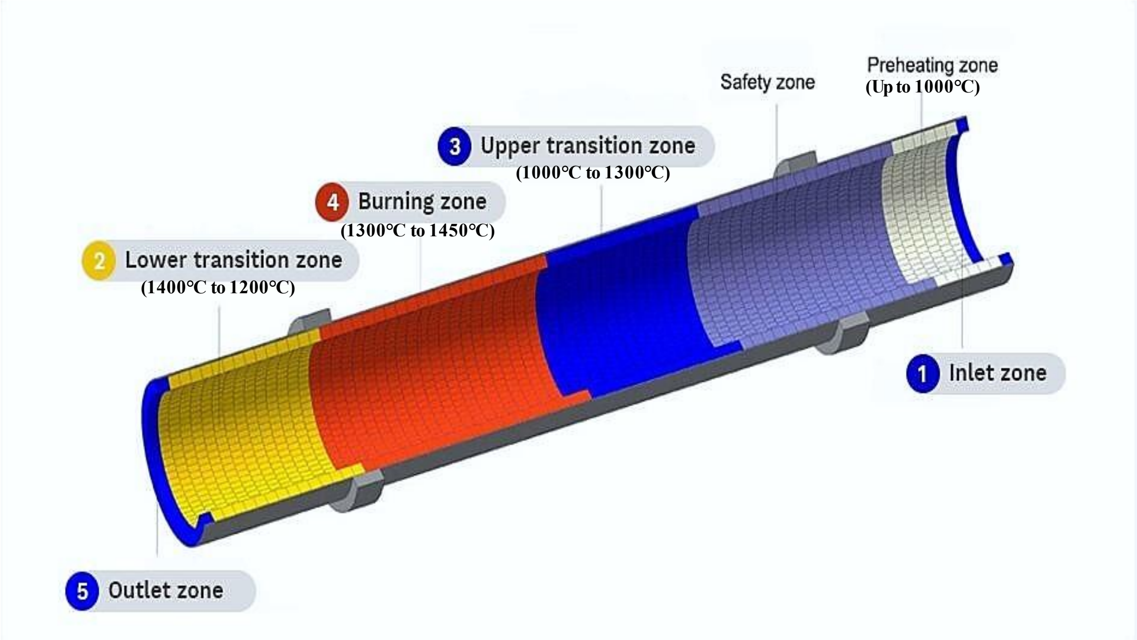


Fig.1.5 Different types of zones in a rotating kiln (Atmaca and Yumrutas, 2014)

1.2.7 Clinker cooling and final grinding

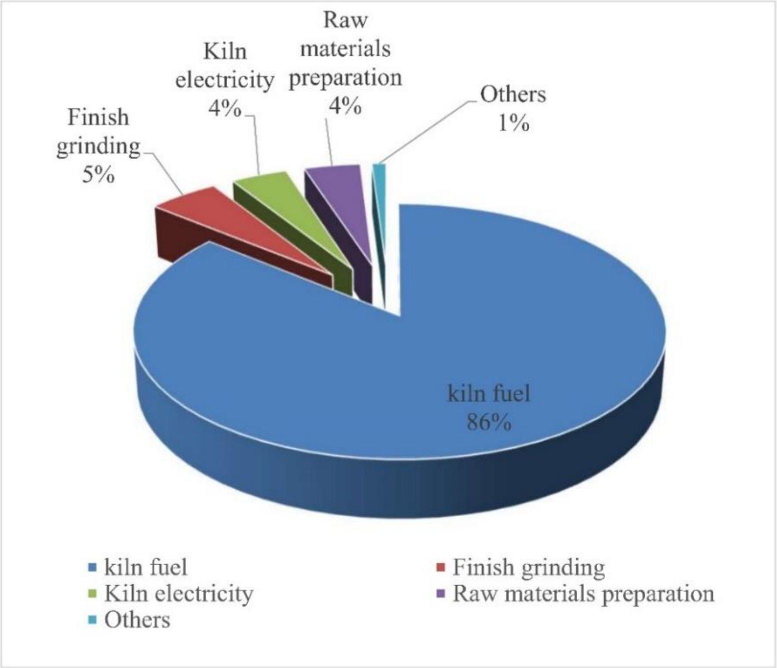
The clinker coming out from the rotary kiln is rapidly cooled down from 2000°C to 100°C-200°C by passing cool air over it. Then various additives are mixed with the clinker to be ground in order to produce the final product, cement. Gypsum is the most commonly added additive which is added to regulate the compressive strength and setting time of the cement. The grinding operation in the cement mill is carried out with the help of metallic balls (Zeman, 2009).

1.2.8 Packing and shipping

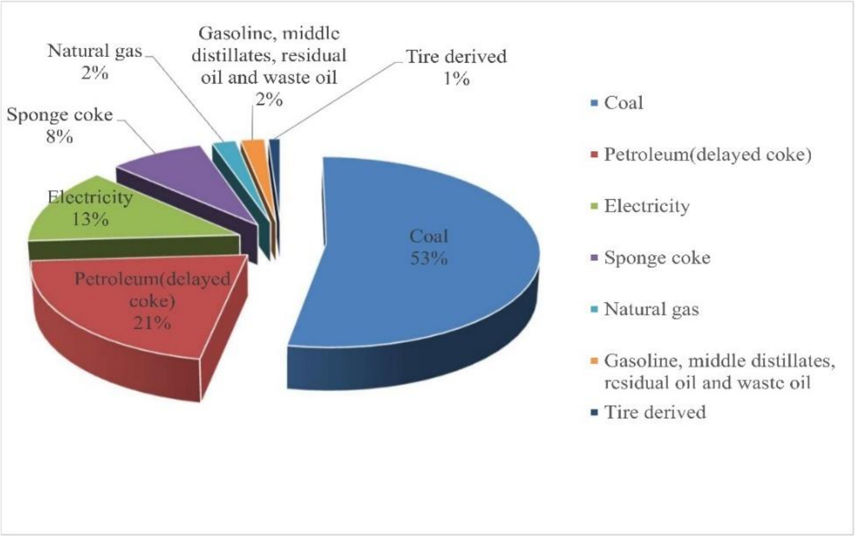
The last and final step of cement manufacturing is packing and shipping. Large, vertical silos are used to store cement. Most cement is often transported by trucks, trains, or ships and few quantities are bagged for retail sale for clients who need modest quantities. The transport methods are the same as those used for bulk transport cement.

1.3 ENERGY CONSUMPTION IN CEMENT PRODUCTION

Technology is the key factor in deciding the value of specific energy consumption in cement production. The dry process of cement manufacturing uses more electrical energy than the wet process, while the wet process uses more thermal energy than the dry process. The dry process utilizes 75% thermal energy and 25% electrical energy in cement production. The major percentage of thermal energy generated from the combustion of fossil fuel is utilized for the production of clinker. It is reported that the cement industry utilizes 90% of the total consumed natural gas for clinker production in large rotary kilns (Fig. 1.6). For Indian cement industries, coal fulfills ninety-four percent of the thermal energy demand, while the remaining demand is fulfilled by fuel oil and high-speed diesel oil. Cement industry in India does not have sufficient natural gas available (Karwa et al., 1998). In California, a small white cement plant uses natural gas as its main fuel in the kiln system. Moreover, the other uses of the natural gas are in the boiler and machine drive end uses (KEMA, 2005).



(a)



(b)

Fig.1.6 Energy utilization (a) for different processes and (b) electrical energy by energy source in cement manufacturing process (CIPEC, 2009)

However, electrical energy is mostly used for crushing and grinding purposes. The crushing of raw materials utilizes 33% of total electrical energy, whereas clinker grinding utilizes 38% of total electrical energy. Other uses of electrical energy include running motors of the kiln system, air blowers of combustion system and fuel supply, etc. Fig.1.7 represents electrical energy utilization for different processes of cement production.

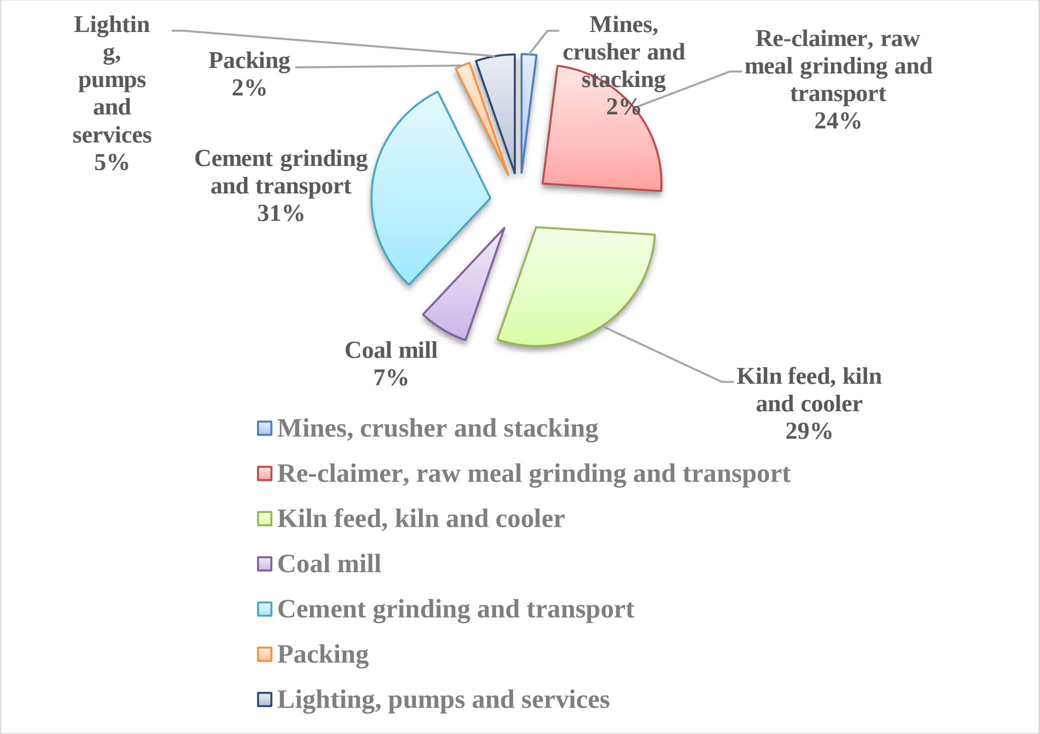
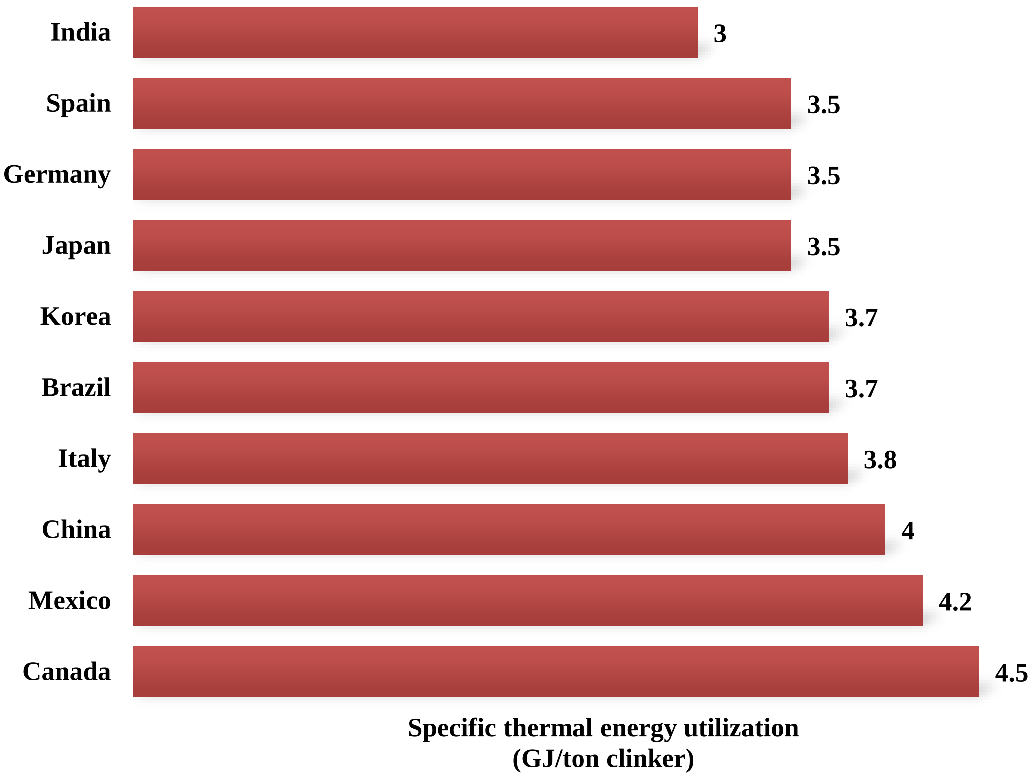


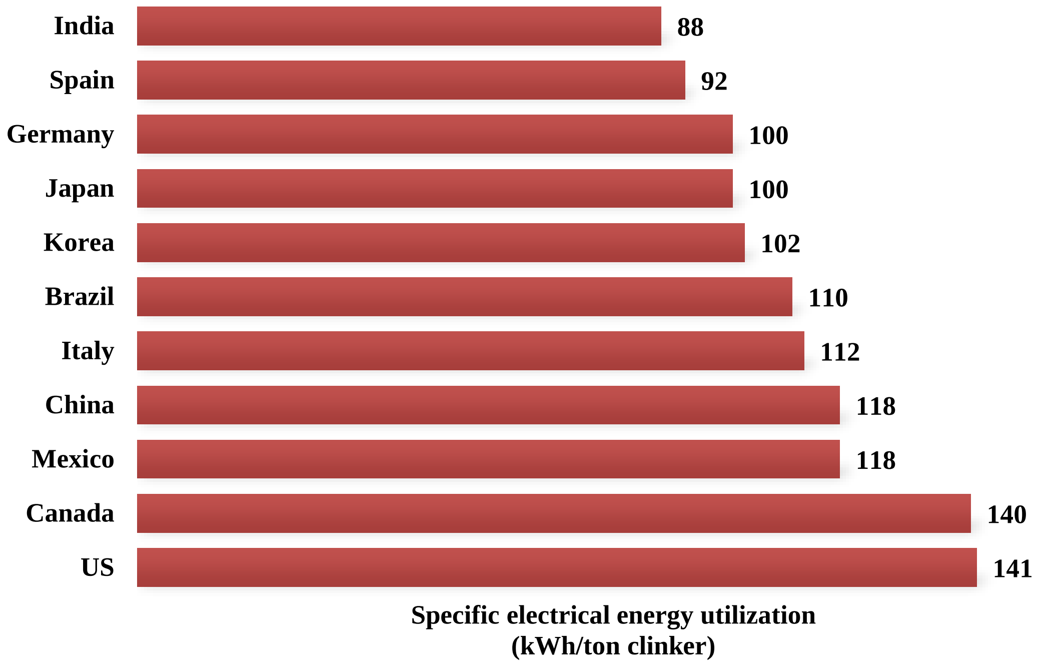
Fig.1.7 Electrical energy sharing in cement industry (Energy Efficiency Asia, 2020)

Clinker production consumes a huge amount of energy and plant efficiency can be improved by reducing the specific energy consumption of clinker. The type of kiln used during cement production mainly decides the specific energy consumption value. It also decides the quantity of CO_2 emissions to the environment. The dry process of cement manufacturing utilizes 3.40GJ of specific energy per ton of clinker production, while the wet process utilizes 5.29GJ/t. It is reported that the specific energy consumption value for many countries is less than 2.95 GJ per ton of clinker while the minimum value in

India is 3.06GJ (Madlool et al., 2011; Madlool et al., 2012; Ahamed et al., 2012). The higher value of specific energy consumption in India may be due to many factors, including harder raw materials and low fuel quality (Kamal, 1997). Thermal and electrical energy required to produce one ton of clinker for some of the selected countries is shown in Fig. 1.8 (Cembureau,2009).



(a)



(b)

Fig.1.8. Energy consumption (a) thermal and (b) electrical of some selected countries (Saidur, 2009)

Thermal energy consumption per ton of clinker for different types of clinker production processes is presented in Table 1.1. Energy consumption can be significantly reduced with the use of a pre-heater. The clinker can be preheated from different sources using waste heat. Fig.1.9 demonstrates the energy consumption in various cement manufacturing processes.

Table 1.1 Thermal energy utilization per ton of clinker production

Type of rotary kiln	**Cyclone preheater stages**	**Fuel utilization (GJ per ton clinker)**
Wet kiln	-	5.86–6.28
Long dry kiln	-	4.60
Long dry kiln	1	4.2
Long dry kiln	2	3.8
Long dry kiln	3	3.3

Long dry kiln	4	3.14
Long dry kiln	5	3.01
Long dry kiln	6	< 2.93

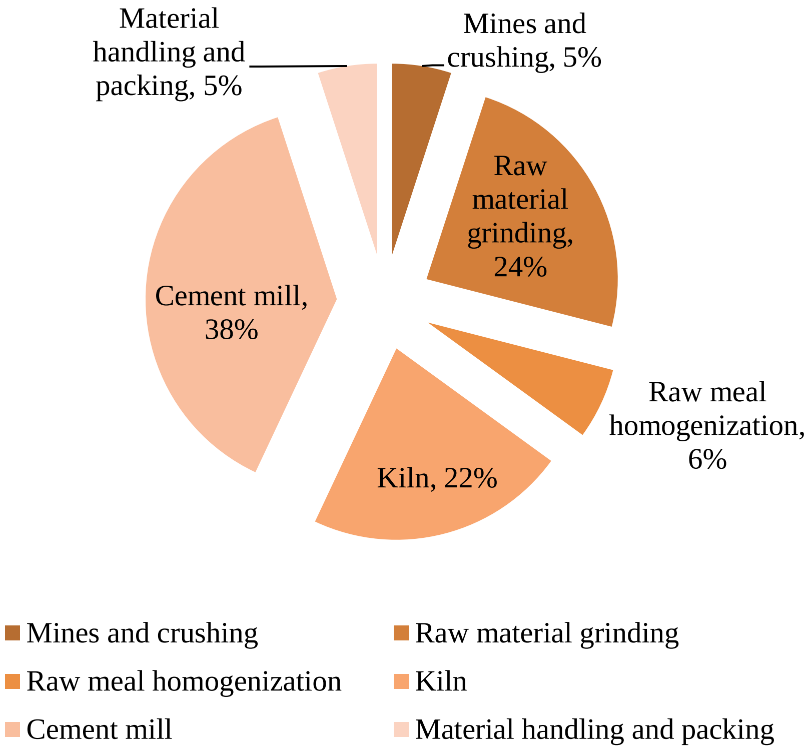
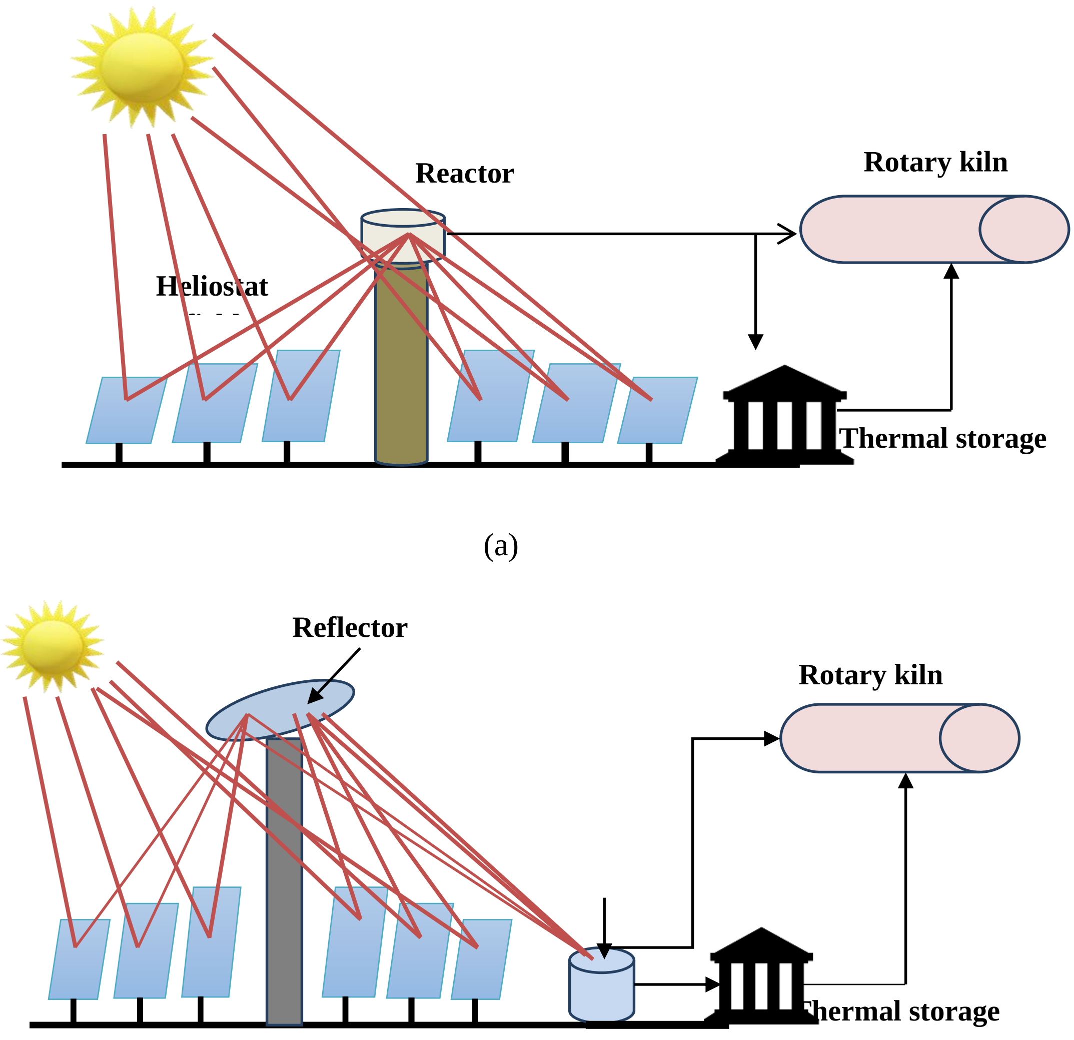


Fig.1.9 Energy utilization for each section of cement manufacturing

In the cement industry, the requirement for thermal energy is mostly fulfilled by the burning of fossil fuels. The most commonly used fossil fuels are coal, diesel, natural gas, fuel oil, petroleum coke, etc. Consumption of these fossil fuels generates a lot of greenhouse gases in the atmosphere. This industry provides around 13% and 8% of the world's total greenhouse gas emissions and anthropogenic carbon dioxide to the environment (Olivier et al., 2012; Change, 2014). As a result, reducing fossil fuel usage is critical while maintaining the cement sector's thermal energy requirements. One best approach to minimize greenhouse gas emissions is to use fewer fossil fuels. This may be done by either increasing system efficiency to use less fossil fuel or by switching to renewable energy sources like solar energy in place of fossil fuel. Enhancing system efficiency is undoubtedly a good strategy, but only for a short period. However, the long-term benefits of solar energy implementation in the cement sector are significant.

1.4 SOLAR CEMENT PLANT

Solar thermal energy can be used to supply heat to the various processes of cement manufacturing through the use of a solar reactor. According to the literature, there are two possible designs for the solarization of the calcination step, as shown in Fig. 1.10. The position of the solar reactor makes the design different.



(a)

(b)

Fig.1.10 Model of solar cement plant (a) solar reactor located on the top and (b) solar reactor located on the bottom (Pitz-Paal et al., 2013)

- Design model one: The solar reactor is placed atop the existing preheater tower. It is also known as top-of-tower (TT) design. Optically, this design is considered superior to other design models because optical losses are low (Falcone, 1986; Romero et al, 2000).
- Design model two: This model is also known as the beam-down (BD) design model due to the solar reactor being fixed on the ground. An additional reflector was used to focus the solar influx on the reactor. The reflector's position is specified on the top of the preheater tower, as shown in Fig. 1.10 (b). In this model, the solar reactor is placed on the ground to supply and maintain raw materials efficiently (Yogev et al., 1998; Kribus, 1997). The major disadvantage of this model is that using an additional reflector leads to many losses in the solar fluxes, and further additional investment is needed for the reflector mirror (Welford and Winston, 1989). Due to this, the TT model is considered superior to the BD model.

The best approach to integrating the CST technology in a conventional cement plant is to use solar tower system with a solar reactor at the top of the solar tower or preheater tower. Additionally, the use of non-conventional sources of energy in cement production reduces a lot of anthropogenic emissions to the atmosphere.

1.5 ORGANIZATION OF THESIS

The overall thesis entitled “Energy Conservation and Emission Reduction Potential through Solar Energy Applications in Cement Industries prepared in five chapters comprising, introduction, literature survey, methodology (i.e., concept of solar cement plant), results and discussion, conclusion, future scope and social impact followed by the references and list of publications. Additionally, the following is a representation of the chapters' overall schemes:

Chapter 1 reflects realistic background of solar industrial process heating in the field of cement production. It defined generalized introduction towards cement manufacturing processes with nature of energy requirement. This chapter offers a better understanding of cement production as well as the concept of implementation of concentrated solar energy. Further, possible designs for the solarization of the calcination step have been discussed.

Chapter 2 establishes a vital stage of different energy conservation and emission reduction opportunities in cement production (historical background to latest developments) along with a brief glimpse of solar industrial process heating technology. This section also discusses in detail the literature related to solar calcination reactors. Further, the prototype reactors built for solar calcination reactions have been discussed along with thermal modelling, economic analysis and environmental assessment. In this chapter, the problem statement has been identified with the proposed research gap and targeted objectives for the present research work that has been carried out at the Delhi Technological University (DTU), Delhi. Also, the research scope and research contribution to society have been presented in this chapter to justify the goodness of this technology towards society and thus the nation.

Chapter 3 sets the analytical methodology with sequential steps to achieve the research objectives as mentioned in chapter two. The concept of solar cement plant design has been done. Solar and thermal energy needed to run the solar reactor for the calcination of raw material in cement production using a heat balance equation has also analyzed. Energy conservation potential for Indian cement manufacturing industry has been assessed by identifying the nation’s cement plants, finding out the annual production capacity and actual production of each plant and evaluating the annual thermal energy requirements for calcination process of each plant (i.e. gross SIPH potential). Then a conventional cement plant (Kotputli Cement Works (KCW), an UltraTech Cement Limited manufacturing unit) at Kotputli, Jaipur, Rajasthan, was investigated for solar thermal application. Economic feasibility of the model is determined through the payback time (PBT) and the internal rate of return (IRR) criteria.

Chapter 4 contains the results and discussion for the proposed solar system that comprise the evaluation of state-wise annual thermal energy needs of clinker production based on conventional and suggested (solar) systems along with state-wise reduction of CO_2 emissions. In addition, this section discusses the findings of solar thermal application of the investigated plant. Power required for the calcination reaction and energy out from the solar reactor have been calculated. Result includes the required mirror surface, number of heliostats, land surface, solar energy flux and net efficiency of the process. All these calculations are done by assuming the thermal losses as 15, 30 and 45 percent. Further, a PBT and IRR have been calculated for the plant under study.

Chapter 5 represents the conclusion of the entire observations made for the proposed solar system in this Thesis. Further, all of the observations have been concluded with suggestions for future research that would encourage the researchers to continue looking into possible improvements in this area for the benefit of the environment and society.

The next chapter establishes a vital stage of different energy conservation and emission reduction opportunities in cement production (historical background to latest developments) along with a brief glimpse of solar industrial process heating technology. This section also discusses in detail the literature related to solar calcination reactors. Further, the prototype reactors built for solar calcination reactions have been discussed along with thermal modelling, economic analysis and environmental assessment. In this chapter, the problem statement has been identified with the proposed research gap and targeted objectives for the present research work that has been carried out at the Delhi Technological University (DTU), Delhi. Also, the research scope and research contribution to society have been presented in this chapter to justify the goodness of this technology towards society and thus the nation.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Over the past two decades, the cement industry has implemented a number of initiatives to promote energy saving and emission reduction. By minimizing waste and losses, enhancing efficiency through technological advancements, and improving operation and maintenance, energy may be conserved. Using less energy to deliver the same service or output without sacrificing productivity or product quality is referred to as energy conservation. The cost of cement production can be reduced by improving energy efficiency. Improvement may be attained by applying more energy-efficient techniques to the production process and the processes that support production. In cement production, there are three major steps: making raw meal, clinker production, and finishing grinding of clinker to produce cement powders. Raw meal preparation and clinker production can be done by wet or dry process. Most of the cement production industry uses the dry process. Energy conservation and emission reduction opportunities for cement production are as follows:

2.2 RAW MATERIAL PREPARATION

The energy (thermal and electrical) conservation opportunities and carbon dioxide (CO_2) emission reduction in raw materials preparation are represented in Table 2.1. Each technology used for energy conservation and emission reduction is given as.

2.2.1 Energy-efficient transport system for raw meal preparation (dry process)

Conveyors are a preferable transport system in cement industry. It is used for transporting kiln dust, final cement powder and feeding raw materials to the kiln system. Conveyors may be pneumatic or mechanical type. Among these two types of conveyors, the mechanical one uses less energy in comparison to pneumatic type and it was estimated that there was an energy saving of 3.40 kWh/ton raw material with adaption of mechanical type conveyor system (Price et al., 2008). Many studied the energy-efficient transport system and have estimated that an energy efficient transport system greatly reduces energy/fuel consumption and CO_2 emissions (Worrell et al., 2000; Price et al., 2008; Hasanbeigi et al., 2011; Price et al., 2009; Hasanbeigi et al., 2010).

2.2.2 Efficient blending system (dry process)

For efficient burning of the raw material in the kiln it should be completely mixed so that they are homogenized entirely. A homogenized raw material also produces good quality cement. For blending raw meal, gravity type silos or air-fluidized type silos are used. Gravity type silos consume less energy in comparison to air-fluidized type silos. The documented value of thermal energy savings was 0.02–4.30GJ, while the electrical energy was 0.01–2.66 kWh/t and the CO_2 emission was 0.26–2.73kg/t, respectively (Worrell et al., 2000; Kamal, 1997; Price et al., 2008; Hasanbeigi et al., 2011; Price et al., 2009; Hasanbeigi et al., 2010). On the other hand, Hendriks et al. (1998) found that there will be savings in the electric energy and the estimated value of 1.4 to 4kWh/t.

2.2.3 Use of advanced roller mills (dry process)

If grinding of raw material and coal is done with the help of some advanced roller mills like horizontal, high pressure and high efficiency roller mills then electricity can be saved. If a vertical/horizontal roller replaces a traditional ball mill, the energy saving is estimated to be 6–7 kWh/ton of raw materials (Madlool et al., 2012). Efficiency of the roller mill can be improved by using waste heat from the kiln for drying and grinding raw materials (Venkateswaran and Lowitt, 1988). The documented value of thermal energy saving was 0.08–0.114GJ/t while the electrical energy saving was 6–11.9kWh/t and CO_2 emission was 1.24–10.45kg/t (Worrell et al., 2000; Madlool et al., 2012; Price et al., 2008; Hasanbeigi et al., 2011; Price et al., 2009; Hasanbeigi et al., 2010).

2.2.4 Use of high-efficiency separators/ classifiers (dry process)

The main function of classifier is to separate the coarse particle from fine particle. Over grinding is a major issue during the grinding of the raw material and it should be avoided because it unnecessarily consumes electricity. The use of a separator/classifier is a recent grinding technology in which classifiers are used to separate the coarse particle from the fine particle. There will be an 8% reduction in electrical energy consumption if high efficiency classifiers are used in cement plant (Holderbank, 1993). Shapiro and Galperin, 2005 also analyzed the techniques, features, and scope of using modern air classifier devices. It was also reported that there would be savings in electrical energy and the documented value was 2.8 to 3.7 kWh/t of raw material (Süssegger, 1993; Salzborn and Chin-Fatt, 1993).

2.2.5 Blending and homogenization of slurry (wet process)

Cement industries use batch processes for slurry blending and homogenization. Compressed air and rotating stirrers are used for mixing. The performance of compressed air is very poor and also a lot of energy loss. An effective mixing system can utilize 0.3 – 0.5 kWh/t of raw material (Madlool et al., 2012). Energy efficiency of slurry blending systems can be improved by using a compressed air system. By optimizing the compressed air system, the documented reduced value of CO_2 emission was 0.2–0.3kg/t (Price et al., 2008).

Table 2.1 Energy conservation opportunities in raw materials preparation

Energy conservation step	**Technology used**	**Thermal energy saving (GJ/tonne)**	**Electrical energy saving (kWh/tonne)**	**Emission reduction (kgCO_2/tonne)**	**Reference**
Efficient transport system (dry process)	Mechanical type conveyors use less energy in comparison to pneumatic	0.02	-	0.53	(Worrell et al., 2000)
		-	3.40	0.78	(Price et al., 2008)
		0.03	2.54	0.41	(Hasanbeigi et

	type				al., 2011)
		0.035	3.13	3.22	(Price et al., 2009;)
		0.03	-	1.3	(Price et al., 2008; Hasanbeigi et al., 2010)
Efficient blending system (dry process)	Gravity type silos consume less energy in comparison to air-fluidized type silos	0.10	0.01	0.26	(Worrell et al., 2000)
		1.70-4.30	-	0.4-1.0	(Price et al., 2008)
		0.03	2.29	-	(Price et al., 2008; Hasanbeigi et al., 2011)
		0.03	2.66	2.73	(Price et al., 2009;)
		0.02	2.14	1.11	(Price et al., 2008; Hasanbeigi et al., 2011)
Adaption of advanced roller mills (dry process)	Old ball mills should be replaced with advanced roller mills Drying and grinding of raw materials using kiln waste heat	0.08	-	1.85	(Worrell et al., 2000)
			10.2-11.9	2.3-2.7	(Price et al., 2008)
		0.09	7.63	1.24	(Price et al., 2008; Hasanbeigi et al., 2011)
		0.114	10.17	10.45	(Price et al., 2009;)
		0.09	8.7	4.24	(Price et al., 2008; Hasanbeigi et al., 2011)
Use of high-efficiency separators/ classifiers (dry process)	Use of separator/classifier is a recent grinding technology in which classifiers are used to		8%	-	(Holderbank,1993)
		0.03	-	0.71	(Worrell et al., 2000)
		0.04	3.18	0.51	(Hasanbeigi et al., 2011)
		0.57	5.08	5.23	(Price et al., 2009;)

	separate the coarse particle from the fine particle.	0.05	4.08	2.12	(Price et al., 2008; Hasanbeigi et al., 2011)
Proper blending and homogenizing of slurry (wet process)	-	-	0.5-0.9	0.1-0.2	(Price et al., 2008)
Grinding of raw material components separately			0.8-1.7	0.4-0.9	(CSI, 2017; Morrow et al., 2014; Hasanbeigi et al., 2013)
Raw material substitution	Granulated blast furnace slag, mine rejects, red mud, cement kiln dust, etc	0.09-0.36		Up to 100	(MINES, 2018; Cadez and Czerny, 2016; Change, 2014)

2.3 CLINKER PRODUCTION PROCESS

Table 2.2 shows the summary of energy conservation opportunities in clinker production process. A few techniques can be applied to increase energy efficiency during clinker production. Some of the available techniques are discussed as follows:

2.3.1 Improved refractoriness in the kiln shell

Refractories are used to insulate the kiln shell so that heat lost from the kiln surface can be reduced. The selection of proper refractory material depends upon certain parameters like raw meal type, operating conditions and type of fuel used, etc. This technique saves 0.12– 0.63 GJ/t of thermal energy and 10.3–15.5kg/t of CO_2 emission (Price et al., 2008; Lowes and Bezant, 1990; ITIBMIC, 2004). A large amount of heat from burning zone of kiln is lost to atmosphere through the kiln's surface. Venkateswaran and Lowitt (1988) examined that heat loss can be reduced through proper use of improved insulating refractory material on the kiln surface.

2.3.2 Improvement of cooler system in clinker making process

Cooling of the clinker is done with the help of cooler. For this purpose, four types of coolers are used: planetary, rotary, shaft and reciprocating grate coolers respectively. In old kilns, satellite coolers are used for cooling purposes. If modern reciprocating grate coolers replace it, the efficiency of heat recovery can increase with a decrease in fuel consumption. Holderbank estimated an energy saving of 0.14MBtu/ton clinker by replacing the old satellite cooler with reciprocating grate coolers. Vleuten (1994) also reported that the kiln fuel would save more than 8% while Bump (1996) predicted a 3% decrease in specific fuel consumption. Adapting this new type of cooler will result in a 0.19–0.3GJ/t thermal energy saving and a 6.3–20.46kgCO_2/t reduction (Worrell et al., 2000; Price et al., 2008; Hasanbeigi et al., 2010).

2.3.3 Replacement of long-dry kiln system with a preheater/precalciner kiln system

If preheater/ precalciner kilns replace the long dry kilns then there will be a noticeable amount of thermal energy reduction as well as reduction in carbon dioxide emission. By implementing this technology, the thermal energy savings were 0.4–1.4GJ/t and the CO_2 emission reduction was 20.46 and 112.61 kg/t, respectively (Worrell et al., 2000; Price et al., 2008; Hasanbeigi et al., 2010; Holderbank, 1993). Further, the efficiency of a precalcining rotary kiln in a cement production process can be enhanced using a process simulator. Aspen Plus is one such process simulator that estimated optimal energy efficiency of 61.30 % (Okoji et al., 2022).

2.3.4 Upgradation in clinker making system with multi stage preheater kiln

The installation of multistage preheater and pre calciner (four or five stages) in place of one or two stage preheater used in old kilns can minimize the heat losses and improve energy efficiency of the kiln system. Another important feature includes reduction in pressure drop, reduction in fan power and more competence in resuming heat. With adaption of this technology, 0.73–0.9 GJ/t of thermal energy can be saved and also 23–72.39kgCO_2/t emission can be reduced (Worrell et al., 2000; Price et al., 2008; Hasanbeigi et al., 2010; Holderbank,1993). Duplouy and Trautwein (1997) also found that increasing the number of stages in the preheater system can reduce the specific fuel consumption and the documented value with this respect was from 4.1 to 3.6 GJ/t.

2.3.5 Improvement of kiln combustion system

A kiln performance can be improved by adjusting the firing, and partial replacement of the fossil fuel with some other fuel like waste type biomass, waste fuels, etc. Lowes and Bezant (1990) highlight the advancement in combustion technology, which addresses the issues. Firing is an important phenomenon in kiln combustion systems. In old cement plants, the primary air and coal are passed directly to the kiln, whereas in modern plants, the firing is done indirectly, which means neither coal nor is primary air passed to the kiln directly (Lowes and Bezant, 1990). Worrell et al. (2000) reported that thermal energy saving and reductions in emissions were 0.015–0.22 GJ/t and 0.39–0.57kgCO_2/t, respectively. The use of alternative fuels can increase the kiln's effectiveness in a cement factory. By switching to a fuel made of a mixture of rice husk and waste-derived material in place of coal, 13% of electrical energy use may be saved (El-Salamony et al., 2020). Evaluation was done on the usage of oil sludge as a substitute fuel for clinker production. Additionally, it was shown that oil sludge could substitute coal in a proportion of 90.98% (Huang et al., 2017). At the Balcones factory in San Antonio, Texas, Bourtsalas evaluated the use of shredded non-recycled plastics and paper scraps as an alternate fuel for cement manufacture. By replacing high-quality coal with this alternative fuel, the cement industry may cut greenhouse gas emissions by up to 3 tonnes of CO_2 per tonne of alternative fuel (Bourtsalas et al., 2018). Another study sought to produce high-calorie refuse-derived fuel (RDF) from biomass (sawdust, paddy husk, and empty fruit bunch) and hazardous waste mixtures (rubber waste, mixed trash, paint sludge, palm oil sludge, and wastewater treatment plant sludge). It has been investigated if freshly produced RDF may take the place of coal as a fuel in the production of cement. This study revealed that replacing 5 tonnes per hour of RDF for coal results in NOx emissions of just around 301 mg/m3 and a CO_2 reduction of roughly 2.25 kg per kilogram (Karpan et al., 2021). Wood derived fuel (WDF) is an alternative option for cement industry. It has been claimed that 16% of CO_2 emission reduction can be possible while using 20% WDF as co-fuel (Hossain et al., 2019). A carbonaceous substance called spent pot lining (SPL) is produced during the initial stages of the aluminum smelting process. SPL is a dangerous waste, yet it has a lot of energy density. The cement industry may use properly prepared SPL fuel as an alternative fuel, and it also produces less pollution than traditional fuel (coal) (Ghenai et al. 2019).

2.3.6 Up-gradation of the kiln drive for clinker making

The rotation of kiln requires a considerable amount of power. Among the kiln drives, the single pinion kiln drive is the most efficient one (Regitz, 1996). Adapting this modern kiln drive can contribute 0.005–0.006 GJ/t of thermal energy savings and 0.45–3.9 kW h/t of electrical energy savings. And there is also 0.13–0.9kgCO_2/t emissions reduction (Price et al., 2008; Price et al., 2009; Hasanbeigi et al., 2010).

2.3.7 Use of low pressure drop cyclone

Cyclones are the most fundamental elements of the preheating system. The electricity consumption of the gas fan system can be reduced by replacing the older cyclones with low pressure drop cyclones. Adapting this technology can save 0.02–0.04 GJ/t of thermal energy and 0.66–4.4 kW h/t of electrical energy. Also, this type of low pressure drop cyclone contributes 0.16– 2.67 kgCO_2/t emission reduction (Worrell et al., 2000;

Madlool et al., 2012; Price et al., 2008; Hasanbeigi et al., 2011; Price et al., 2009; Hasanbeigi et al., 2010; Fujimoto, 1994; Birch, 1990).

2.3.8 Waste heat recovery for power generation

The temperature of the gas discharged from the rotary kiln and clinker cooling system is very high. This waste gas can be used for raw material drying and power generation. By adopting this technique, the estimated value of thermal energy saving, electrical energy saving and emission reduction were 0.21–0.22 GJ/t, 17.84–22kWh/t and 3.68–9.25kgCO_2/t respectively (Worrell et al., 2000; Madlool et al., 2012; Price et al., 2009). The waste heat from the cement rotary kiln can be utilized for calcining phosphogypsum. This technique saved fossil fuel which has been used for the processing of phosphogypsum (Mittal and Rakshit, 2020). It may be possible to increase energy efficiency to make cement manufacturing cleaner and more sustainable by recovering heat from the kiln shell surface. The use of infrared thermography technology can save 12 % of the energy input into the rotary kiln (Wu et al., 2019).

Table 2.2 Energy conservation opportunities in clinker production

Energy conservation step	**Technology used**	**Thermal energy saving (GJ/tonne)**	**Electrical energy saving (kWh/tonne)**	**Emission reduction (kgCO_2/tonne)**	**Reference**
Improved refractoriness in the kiln shell	Selection of proper refractory material for insulating the kiln shell	0.12-0.4	-	-	(Lowes and Bezant, 1990)
		0.46-0.63	-	-	
		0.4-0.6	-	10.3-15.5	(Price et al., 2008)
Improvement of cooler system in clinker making process	Replacement of satellite coolers in old kilns with modern reciprocating grate coolers.	>8%	-	-	(Vleuten, 1999)
		3%	-	-	(Bump, 1996)
		0.3	-	16.37	(Worrell et al., 2000)
		0.27	-	6.3	(Price et al.,

					2008)
		0.22	-	20.46	(Hasanbeigi et al., 2010; Price et al., 2008)
Replacement of long-dry kiln system with a preheater/ precalciner kiln system	Replacement of long-dry kiln system with a preheater/ precalciner kiln system	1.4	-	-	(Holderbank, 1993)
		0.4	-	20.46	(Worrell et al., 2000)
		1.4	-	36	(Worrell et al., 2000)
		1.14	-	112.61	(Hasanbeigi et al., 2010; Price et al., 2008)
Upgradation in clinker making system with multi stage pre heater kiln	Installation of multistage pre heater and pre calciner (four or five stages) in place of one or two stage preheater	4.1-3.6	-	-	(Duplouy and Trautwein, 1997
		0.9	-	-	(Holderbank, 1993)
		0.9	-	46.05	(Worrell et al., 2000)
		0.9	-	23	(Price et al., 2008)
		0.73	-	72.39	(Price et al., 2008; Hasanbeigi et al., 2010)
Improvement of kiln combustion system	Adjustment in firing and partial replacement of the fossil fuel with some other fuel like waste type biomass, waste fuels etc.	2-10%	-	-	(Venkateswaran and Lowitt, 1988)
		>10%	-	-	(Lowes and Bezant, 1990)
		5-10%	-	-	(CADDET, 1997)
		2.7-5.7%	-	-	(Vidergar et al.,1997)
		0.17	-	8.8	(Worrell et al., 2000)
		0.1-0.5	-	2.6-12.9	(Price et al., 2008)
		0.24	-	24.13	(Price et al., 2008;

					Hasanbeigi et al., 2010)
Up gradation of firing system for clinker making	Indirect way of firing	0.015-0.022	-	0.39-0.57	(Price et al., 2008)
Up gradation of the kiln drive for clinker making	Upgrading to single pinion kiln drive system	-	0.55-3.9	0.13-0.9	(Price et al., 2008)
		0.006	0.55	0.57	(Price et al., 2009)
		0.005	0.45	0.23	(Price et al., 2008; Hasanbeigi et al., 2010)
Use of low pressure drop cyclones	Replacement of old cyclones with low pressure drop cyclones leads to less electricity consumption	0.04	-	0.74	(Worrell et al., 2000)
			0.7-4.4	0.16-1.0	(Price et al., 2008)
		0.04	3.28	0.53	(Hasanbeigi et al., 2011)
		0.029	2.6	2.67	(Price et al., 2009)
		0.02	2.11	1.09	(Price et al., 2008; Hasanbeigi et al., 2010)
Waste heat recovery for power generation	Waste heat from the discharged gas can be used for raw material drying and power generation	0.22	-	3.68	(Worrell et al., 2000)
			22	5.1	(Worrell et al., 2000)
		0.21	17.84	9.25	(Price et al., 2008; Hasanbeigi et al., 2010)
Replacement of seals in rotary kilns	Frequent inspection and proper sealing of the entry and exit points of the kiln	4%	-	-	(Philips and Enviro-Seal, 2001)
		0.011	-	0.3	(Price et al., 2008)
Use of new Suspension Preheater/Preca	Introduction of new Suspension	2.4	-	-	(Liu et al.,1995)
		2.4	-	62	(Price et al.,

lciner Kilns	Preheater/Precalciner Kilns in place of vertical shaft kilns				2008)
Clinker substitution	Some other industry's byproducts GBFS, fly ash, pozzolanas, limestone, lime sludge, lead-zinc slag, phosphorus furnace slag, silica fume, etc	Up to 1.4		Up to 390	(CSI, 2017; Shwekat and Wu, 2018; Salas et al., 2016; Ishak and Hashim, 2015)
		Up to 0.32	2.0-15	Up to 90	
		Up to 0.32	Up to 3.0	Up to 90	
		Up to 0.32	Up to 5.0	Up to 88	
Modern burner	Modern multichannel burner	0.02-0.06		2.2-6.5	(CSI, 2017; Ishak and Hashim, 2015; Carrasco et al., 2019; Benhelal et al., 2013)

2.4 CEMENT GRINDING PROCESS

In the cement industry, the grinding process is applied in making the fine products of raw meal, coal and clinker. The grinding process utilizes 70% of total electricity consumed in a cement production plant (Batra et al., 2005). Therefore, it is necessary to optimize the method of grinding process. An optimized grinding process produces finer cement products with less energy consumption. Table 2.3 shows the summary of energy conservation opportunities in cement grinding process. A description of each technology used for energy conservation is as follows:

2.4.1 Up-gradation of mill for finish grinding

The grinding process of cement production consumes a considerable amount of power which depends on several parameters like the hardness of raw materials, type of mill, etc. Older cement plants have traditionally used ball type mills while new plants use vertical type roller mills (VRM). The advantages of VRM over ball mill include 20% reduction in thermal energy consumption, good energy saving potential, and operating on materials containing moisture up to 20%. Due to its high potential, it is generally used for clinker grinding process. The documented values of thermal energy and electrical energy savings are 0.2–0.29 GJ/t and 10–25.93 kWh/t. Additionally, reduction of emission has been documented to be 8.82–26.66kgCO_2/t (Madlool et al., 2012; Hasanbeigi et al., 2011; Price et al., 2009; UNFCCC, 2008; Schneider, 1999; Simmons et al., 2005). It has also been documented that the use of VRM reduces operating costs. Wustner (1986) estimated a 30% of energy could be saved by using high pressure grinding rolls (HPGR) and Patzelt (1992) have been documented an energy-saving of up to 10-15%. The cost of operation was also less than the conventional ball mills (Abouzeid and Fuerstenau, 2009; Van der Meer and Gruendken, 2010). Bhatty et al. (2004) and Conroy (1989) have estimated energy savings of up to 7–30% using HPGR. For this measure, the documented value of savings was 0.09–0.31 GJ/t for thermal energy, 8–28 kW h/t for electrical energy and 1.28–25.09kgCO_2/t for emission reduction (Worrell et al., 2000; Madlool et al., 2012; Price et al., 2008; Hasanbeigi et al., 2011; Price et al., 2009).

2.4.2 Improvement of grinding media & circuit

The selection of grinding media mainly depends on the material wear characteristics. Wear and energy consumption can be reduced by increasing the balls' surface hardness and charge distribution. By adopting this technique, the estimated value of electrical energy and energy/fuel saving was to be 0.02–0.068 GJ/t and 1.8–6.1 kW h/t, respectively. Additionally, 0.29–6.27kgCO_2/t amount of emission can be reduced (Worrell et al., 2000; Madlool et al., 2012; Price et al., 2008; Hasanbeigi et al., 2011;

Price et al., 2009; Venkateswaran and Lowitt, 1988). The quality of the cement powder and energy consumption can be enhanced by improving the cement grinding circuits. Dry stirred milling is one such technology used in cement industry. Altun (2020) evaluated the applicability of this technique and found that by implementing this technique 7 to 18% of energy can be saved and 2.8% of cement quality powder can be improved. Additionally, simulation methods are crucial for defining the optimization potential. A pre-feasibility for the intended activity is provided by such a method before the actual applications are started. The cement powder's quality and energy efficiency can be upgraded by changing the cement grinding circuit's current flowsheet. The production rate improved by 4.45 percent when the mill filter stream, which was initially intended for the classifier feed, was sent to the final product silo. This translated to an energy savings of 4.26 percent (Altun, 2020).

Product quality improvement, fuel consumption reduction and uniform cement particles can be possible by introducing high efficiency classifiers/separators in the ball mill system. A reduction in electricity consumption is also documented as 1.90–7.00 kW h/t (Holderbank, 1993; Salzborn and Chin-Fatt, 1993; Parkes, 1990). Additionally, the energy/fuel saving, electrical energy saving & reduction of emission have been documented to be 0.04–1.62 GJ/t, 7.00 kW h/t and 0.4–2.07kgCO_2/t respectively (Worrell et al., 2000; Price et al., 2009; Price et al., 2008; UNFCCC, 2008; Van den Broeck, 1999).

2.4.3 Improved process control and management

To obtain better quality of cement, the flow of materials must be regulated by the control system. An energy-saving of 2.5-10% is to be estimated by applying this measure (Van den Broeck, 1999; Goebel, 2001). Lauer (2005) also documented a 2% reduction in energy consumption by adapting this technique.

2.4.4 Upgradation in grinding aid

In order to ensure an effective comminution process, grinding aids, typically amine group compounds, are employed to decrease agglomeration and boost concrete strength. Polymer-based innovative grinding aids can boost grinding performance by 30% to 32% while decreasing energy usage by 7% to 9% (Dengiz Özcan et al., 2022). Another grinding aid that improves the performance of ground cement are Polycarboxylate-based grinding aid. It improves the grinding efficiency as well as mechanical properties of the cement powder (He et al., 2021). A new research study suggests that waste cooking oil (WCO) can safely be used as a grinding aid. The findings indicate that WCO generally enhances cement grinding as well as increases cement strength (Li et al., 2016). Granulated blast-furnace slag can be used as an alternative to Portland cement. It has lower carbon emissions and also improves grinding efficiency (Zhang et al., 2020). The idea of using polycarboxylate ether/ester (PCE) superplasticizers as a grinding aid for cement is an intriguing one since they might achieve two objectives for the additive by simultaneously grinding and fluidizing (Yang et al., 2019).

Table 2.3 Summary of energy conservation opportunities in cement grinding process

Energy conservation step	**Technology used**	**Thermal energy saving (GJ/tonne)**	**Electrical energy saving (kWh/tonne)**	**Emission reduction (kgCO$_2$/tonne)**	**Reference**
Adaption of latest efficient technologies in grinding in existing plants	Upgradation of ball mill with vertical rolling mills, high-pressure grinding roller		10-16	7-10	(Fujimoto, 1994; Birch, 1990; Wustner, 1986)
Upgradation of mill for finish grinding	Upgradation of ball mill with vertical rolling mills	0.29	25.93	26.66	(Price et al., 2008)
		0.2	17	8.82	(Cement, 2020; Hasanbeigi, 2008

Improvement of grinding media	Improving surface hardness and charge distribution of the balls.	0.02	-	032	(Worrell et al., 2000)
			3-5	0.7-1.2	
		0.02	1.8	0.29	(Lakshmikanth, 2011)
		0.068	6.1	6.27	(Price et al., 2008)
		0.05	4	2.07	(Cement, 2020; Hasanbeigi, 2008)
Improved high efficiency classifiers/separators	Improved high efficiency classifiers/separators	-	6-7	-	(Price et al., 2009 ;Wustner, 1986)
		-	1.9-2.5	-	(Salzborn and Chin-Fatt, 1993)
		-	0-7	-	(Patzelt,1992)
		0.3	-	0.48	(Worrell et al., 2000)
		-	1.9-6	0.4-1.4	(Price et al., 2008)
Use of horizontal roller mill	Use of horizontal roller mill	35-40%	-	-	(Abouzeid and Fuerstenau, 2009)
		0.3	-	4.33	(Worrell et al., 2000)

2.5 ENERGY CONSERVATION OPPORTUNITIES IN SUPPORT PROCESS

Table 2.4 shows the summary of energy conservation opportunities in the support process. A few techniques can be applied in the support process to increase energy efficiency. Some of the available techniques are discussed as follows:

2.5.1 Improved lighting system

The lighting system's electricity consumption accounts for less than 1.5 percent of the cement industry’s total electricity consumption. The documented energy conservation measures are listed as:

Occupancy sensors can be used for automatic control of lighting systems rather than manual control. It turns off the lights during non-working hours or when a room is empty. The payback period for this sensor is about 1 year (Manufacturers, IAC). By implementing this occupancy sensor, up to 10-20% of energy can be saved (Lauer et al., 2005).

a) If mercury lamps are replaced by high pressure sodium lamps, total lightning energy of the plant would be saved up to 50-60% (Price and Ross, 1989).

b) If traditional fluorescent lamps are changed to high frequency fluorescent lamps, the plant's total energy would be saved by 50%.

c) The factory building should be constructed so that it must have roof skylight; hence daylight can be used as an alternate light source. By applying this measure lighting, energy consumption of the plant would be reduced (Kim and Kim, 2007).

2.5.2 Improved air compressor system

Generally, the air compressor system consumes less electrical energy in the cement industry. However, it should work efficiently to maintain the pressure in the air compressor line otherwise, it consumes higher electrical energy. The suggested energy conservation measures are as follows:

a) The operating temperature and pressure of air compressor system can be maintained through regular maintenance. Regular and adequate maintenance also improves compression efficiency and reduces air leakage, which ultimately leads to energy savings.

b) Leakage is a prominent problem with air compressor systems. Due to leaks, the efficiency of air tool and equipment life deteriorates, which ultimately leads to energy losses. The plants in which regular maintenance work is not done can have a leak rate of 20-50%, which can be reduced to 10% with regular maintenance (Price and Ross, 1989; Rand, 2001). It was also documented that with regular maintenance of air compressor systems, energy consumption can be reduced by 20% (CADDET, 1997; Blaustein and Radgen, 2001).

c) It is also important to choose the appropriate size of the pipe for the compressor system. An appropriate pipe size can increase leakage and losses. It was also documented that inappropriate pipe diameter raises annual energy consumption by 3% (Blaustein and Radgen, 2001).

2.5.3 High efficiency fans, motors and drives

A significant quantity of power is required by the fans, motors and drive systems in cement manufacturing plant. The documented energy conservation measures are listed as:

a) When replacing old fans with high-efficiency fans, energy use can be saved. The electrical energy savings were estimated for this measure to be 0.11 to 0.7kW h/t (UNFCCC, 2008).

b) A no. of operations is carried out with the help of motors and drives, which includes the movement of fans, rotation of kiln and material transport. It was estimated that energy savings of up to 3-8% can be possible with the implementation of high efficiency motors (UNFCCC, 2008; Hendriks et al., 1998; Price et al., 2008). In cement plants up to 700 electric motors can be found with wide range of power ratings. The electricity consumption can also be reduced by replacing the oversized motors with proper sized motor.

c) The drive system appears in many areas, such as fans of coolers, preheaters and kilns. Electricity can be saved if the old drive system is replaced with variable/ adjustable speed drives. For this measure, the documented value of thermal energy saving was 0.09–0.102 GJ/t, electrical energy saving was 0.08–9.15kWh/ and emission reduction has been estimated to be 1–9.41kgCO_2/ t, respectively (Worrell et al., 2000; Madlool et al., 2012; Price et al., 2008; Hasanbeigi et al., 2011; UNFCCC, 2008).

Table 2.4 Summary of general energy conservation opportunities in support process

Energy conservation step	Description of each step	Thermal energy saving (GJ/tonne)	Electrical energy saving (kWh/tonne)	Emission reduction (kgCO_2/tonne)	Reference
Improved lighting system	Occupancy sensors can be used for automatic control of lighting system	-	10-20%	-	(Lauer et al., 2005)
	mercury lamps are replaced by high pressure sodium lamps	-	50-60%	-	(Price and Ross, 1989)
Proper and adequate maintenance of compressed air system	Reduction of leaks in compressed air system	20%	-	-	(Blaustein and Radgen, 2001)
	Use of correct Pipe Diameter in Compressed Air Systems	20%	-	-	(Blaustein and Radgen, 2001)
	Heat should recover from Air	20%	-	-	(Blaustein and Radgen,

	Compressor Systems for Water Preheating				2001)
High efficiency fans.	Old fans must be replaced with high efficiency models.	-	0.7-0.11	-	(UNFCCC, 2008)
Variable speed drives	Fixed speed models should be replaced with partial or variable speed models	0.08-0.17	-	-	(UNFCCC, 2008)
		0.03-0.1		1.68	(Worrell et al., 2000)
		-	6.00-8.00	1.00-2.00	(Madlool et al., 2012)
		0.09	7.00	1.13	(Price et al., 2008)
		0.102	9.15	9.41	(Hasanbeigi et al., 2011)
High-efficient motors and drives	High-efficient motors and drives	3.00-8.00%	-	-	(Vleuten, 1994; Fujimoto, 1994)
		0.02-0.06	-	0.93	(Worrell et al., 2000)
		-	0-6.00	0-1.3	(Madlool et al., 2012)
		0.31	25	4.05	(Price et al., 2008)
		0.05	4.58	4.7	(Hasanbeigi et al., 2011)
		0.03	3.00	1.56	(Madlool et al., 2012; Price et al., 2009)

Fossil fuel switching	Some low carbon or carbon neutral fuel like heavy oil, natural gas, pure biomass, etc.	Increase of 0.09	40.0-60.0	(CSI, 2017; Ishak. and Hashim, 2015; Huh et al., 2018; Miller et al., 2018)

Cement production utilizes a considerable amount of fossil fuels to fulfill its thermal energy requirements. Coal, Petro coke, natural gas, and biomass are the most commonly used fossil fuels. Moreover, the combustion of fossil fuels releases many toxic gases into the atmosphere. As a result, reducing fossil fuel usage is critical while maintaining the cement sector's thermal energy requirements. One best approach to minimize greenhouse gas emissions is to use fewer fossil fuels. This may be done by either increasing system efficiency to use less fossil fuel or by switching to renewable energy sources like solar energy in place of fossil fuel. Enhancing system efficiency is undoubtedly a good strategy, but only for a short period. However, the long-term benefits of solar energy implementation in the cement sector are significant. One of the best ways to come out of the problem is the use of renewable sources of energy. Solar energy can be effectively used to provide thermal energy for the different processes of cement manufacturing. Calcination is an important process of cement manufacturing and previous research suggested that concentrated solar energy could replace conventional fossil fuel. Solar reactors may be used for calcining the raw materials in cement production. This section discusses in detail the literature related to solar calcination reactors. The review also includes the prototype reactors built for solar calcination reactions. Some of the literature works are described as follows:

Imhof (2000) checked the technical feasibility of incorporating solar energy into a clinker plant having a 3000-ton/day capacity. A combined model consisting of a fossil-fired and a solar-driven calciner was taken. Minimum solar irradiation needed to upgrade the conventional plant was 2000 kWh/m^2. Thermal storage for calcined raw material was not considered, and calciner efficiency was assumed to be 86%. Implementing solar energy in cement production could reduce carbon dioxide emissions by 9% and fossil fuel consumption by 28%.

Meier et al. (2005) checked the economic feasibility of using concentrated solar energy to produce lime. Two designs: TT solar lime plants and BD solar lime plants were verified. The model assessed three input solar incident values (1, 5 and 25 MWth) on the reactors. Author suggested that the plant location having a minimum of 2300 kWh/m^2 Direct Normal Irradiation (DNI) can implement this model. Installation of several heliostats requires a sizable space. When calculating the area, the author used one of the variables as the land usage factor, which was based on the plant's capacity and its geographical location. The required heliostat field land area for a 5 MWth solar lime plant was 24,023 m^2. According to the results, only the 25 MWth plant pays back within eight years of installation, and producing lime using solar energy can avoid 95% of fossil fuel emissions. It is not economically feasible to use concentrated solar energy for small lime plants under 5 MWth unless expenses can be decreased or a higher selling price can be achieved.

González and Flamant (2013) investigated the technical and financial viability of concentrated solar thermal (CST) technology in a conventional cement plant, whose daily production capacity was 3,000 tons of cement clinker. Author proposed and assessed a 40 to 100% replacement of total consumed thermal energy in calciner with concentrated solar technology. Average value of the direct normal irradiance (DNI) considered for designing was 703 W/m^2. Two different approaches are assessed; in the first approach, a heat transfer fluid (gas stream) is heated in the solar receiver to a temperature that allows it to supply enough energy for the calcination reaction. In another approach, the raw meal is directly calcinated by solar energy when fed into a solar reactor. In this approach, two options are possible. Solar reactor can be fixed either at the top of the tower or in the ground. When the solar reactor is positioned at the top of the tower (TT), it is known as the TT system, and when it is placed at the ground, it is known as a beam down (B.D.) system. Since the B.D. technology's state of the art is not yet at the demonstration scale, it is not evaluated. Among these two options, the BD system is more expensive due to the use of secondary reflectors. Analysis considered the TT system with a thermal storage silo storing raw material from the solar calciner at 900°C. Moreover, during the economic feasibility analysis, the author considered the reinforcement cost of the preheater tower and the material transport cost. This solar reactor produces a calcined meal that is further used in cement production and thermal storage. It is operated nine hours per day (on average) to make the calcined material. Land usage and equipment sizing are also evaluated in this research from the heat and mass balances equation. The authors use Meier et al. research to create an equation of scale for determining the solar reactor costs. The cost information, however, solely reflects the cost of the compound's parabolic concentrator (CPC). González and Flamant's work has not considered the reactor cost. As part of this analysis, the compensation time and profitability estimation for the concentrated solar power (CSP) investment were included, and it was concluded that conventional cement plants could employ this technology. PBT and IRR have been calculated based on the thermal losses in the solar reactor. Minimum PBT was found 6yrs when considering 15% thermal losses in the solar reactor and PBT increased to 10.4 yrs. when losses increased by 45%. IRR shows a strong dependency on reactor losses. IRR was calculated 11.4% for 15% losses in the reactor while the value dropped to 5.6% for 45% losses.

Abanades and André (2018) designed and experimentally tested a solar-heated rotary tube reactor for limestone ($CaCO_3$) calcination at 1000°C. Receiver of the reactor is a cavity type for absorbing solar radiation from a concentrating system. Solar reactor can be successfully used for $CaCO_3$ calcination involved in either lime or cement production. Greenhouse gases generated from fossil fuel combustion can be avoided.

Tregambi et al. (2018) evaluated the use of a directly irradiated Fluidized Bed (F.B.) reactor for pre-calcining limestone for clinker production. An array of three short-arc

Xe-lamps with a power output of 4 kW_{el} each, combined with elliptical reflectors, was used to replicate concentrated solar radiation and produce a peak flux at the reactor's center of roughly 3 MW/m^2. The total irradiated power is approximately 3.2 kW. The F.B. thermal profiles analyzed with the help of thermocouples and an infrared (I.R.) camera. Calcination was done when the temperature of the F.B. reached a temperature of 950 °C in an atmosphere containing about 70% CO_2. Using a directly irradiated F.B. reactor represents a practical and robust method to accomplish solar-driven calcination of limestone.

Moumin et al. (2020) investigated the technical feasibility and financial viability of implementing solar calciner in the cement industry. A design of a solar cement factory was proposed based on the solar calciner model proposed by German Aerospace Centre, and the heliostat field was evaluated. Furthermore, the study considered solar calciner's energy balance and investigated various possibilities. Implementing solar calciner technology in the cement industry can avoid 14 to 17% of CO_2 emissions into the atmosphere. Costs of avoiding CO_2 were calculated using a conservative base scenario and ranged from 118 EUR/t to 74 EUR/t, depending on solar irradiance, reactor effectiveness, and solar multiple used. CO_2 mitigation potential for Spain's cement factory through 2050 was also calculated. According to a study of cement plant sites in Spain, 39% of existing plants are situated in regions with enough solar irradiation, making using solar calciner technology possible. It was found that the adaption of solar calciner technology by the cement sectors of Spain could save 2 to 7% of CO_2 emissions by 2050.

2.6 RESEARCH GAP

On the thorough scrutiny of the published work on the cement industries, solar collectors and solar industrial process heating, the following observations have been made:

i. Sufficient efforts have not been undertaken to implement solar energy in the field of the cement industry.
ii. Literature lacks in furnishing the theory about the implementation of solar energy in the production of cement.
iii. Less literature is available to integrate the Solar industrial process heating system with the existing system and optimize the total system.
iv. A lot of approaches are available for energy conservation and emission reduction for cement industry. However, no systematic approach is available for energy saving by implementing solar energy.
v. Solar collector technology for providing process heat at low temperatures is commercially established. However, there are few collector technologies for providing process heat at high temperatures.

2.7 RESEARCH OBJECTIVES

The research gap motivates to contribute ahead in this area to a certain extent that can establish a milestone in the field of solar energy applications in cement production. Based on the research gap, certain research objectives have been framed that can be achieved by the design analysis of the proposed systems. The main objectives of the proposed research are:

i. Identify the energy conservation and emission reduction potential in the cement industry.
ii. To evaluate the energy analysis of cement industries for estimating energy consumption for each process.
iii. To design a solar thermal energy system for providing heat energy for each process partly or fully.
iv. Simulation and modelling of the designed system through the use of different modelling tools.

v. To quantify the energy-saving by implementing solar energy.
vi. To estimate the emission reduction by implementing solar energy.
vii. To study the economic analysis of the solar energy system.

The next chapter sets the analytical methodology with sequential steps to achieve the research objectives as mentioned in chapter two. The concept of solar cement plant design has been done. The solar and thermal energy required to run the solar reactor for the calcination of raw material in cement production has also been analyzed using a heat balance equation. Energy conservation potential for Indian cement manufacturing industry has been assessed by identifying the nation's cement plants, finding out the annual production capacity and actual production of each plant and evaluating the annual thermal energy requirements for calcination process of each plant (i.e. gross SIPH potential). Then a conventional cement plant (Kotputli Cement Works (KCW), an UltraTech Cement Limited manufacturing unit) at Kotputli, Jaipur, Rajasthan, was investigated for solar thermal application. Economic feasibility of the model is determined through the payback time (PBT) and the internal rate of return (IRR) criteria.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

A comprehensive assessment of the solar cement factory is provided in this section. Starting with the design of the solar cement plant (section 3.1), section 3.2 provides information on the thermal energy and land requirements. Next, section 3.3 describes the approach used for energy conservation potential estimation and CO_2 emission reduction potential is assessed in section 3.4, the following (section 3.5) emphasizes the layout of the heliostat field, and section 3.6 the location and DNI data sets used. Section 3.7 describes the energy analysis and plant functioning, and finally, section 3.8 assesses the economic analysis of the model.

3.2 Solar-powered cement plant design

Concept of utilizing solar energy for calcination reaction in the cement plant is shown in Fig.3.1 inspired by earlier research (Gonzalez and Flamant, 2013). Design suggests a hybrid mode of operation for the plant. Sequence of raw material processing in a conventional cement plant involves preheating, pre-calcining, and clink erization. However, in the case of solar operation, the calcination process is done in a solar calciner placed at the top of a solar tower. Heat required for calcination is supplied by solar incident power at the reactor, and the output from the solar reactor is transferred to the rotating kiln or thermal storage unit. Solid lines represent the material flow while the dotted line presents the flue gas flow (Fig.3.1). Thermal storage provides the calcined raw material to the rotary kiln when there is no adequate sunlight for generating solar power or at night when there is no sunlight.

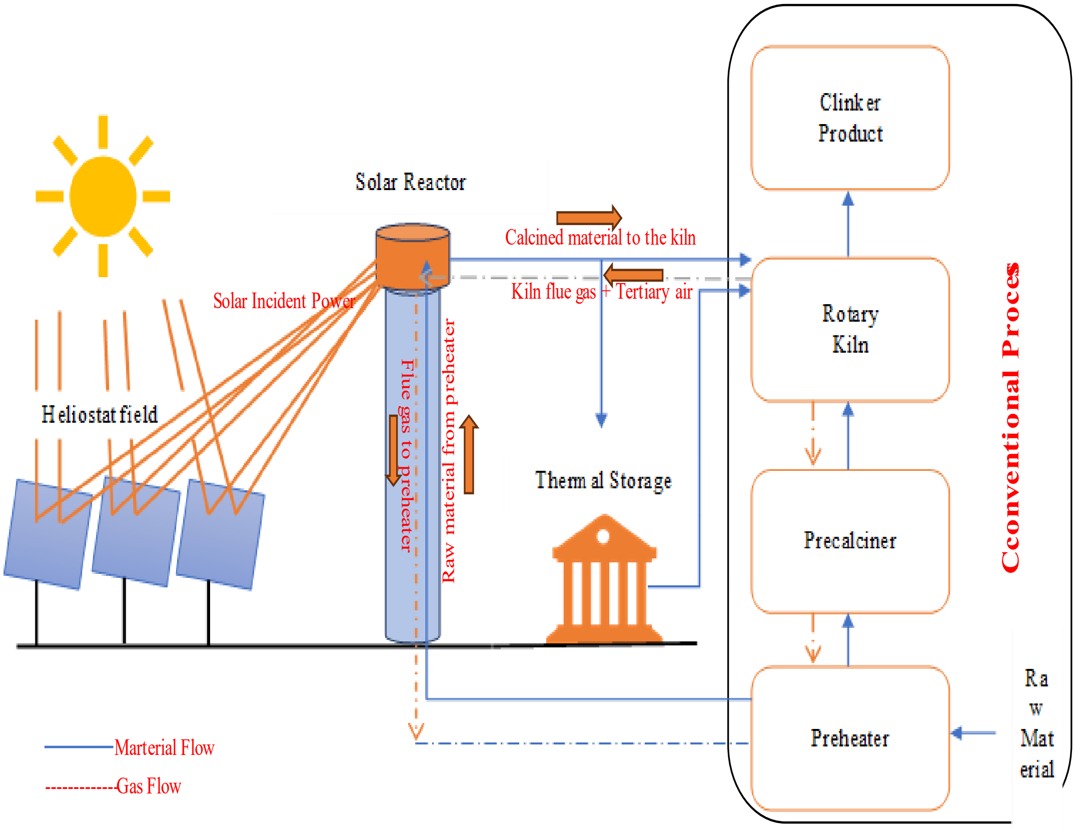


Fig.3.1 Design of a solar-power cement plant

Modifying the conventional cement plant to a hybrid mode requires installing some new equipment. It mainly includes transport systems for transferring the output from the preheater to the solar reactor and the output from the reactor to either the rotary kiln or the storage unit. In order to reach the high temperature needed for the calcination reaction, a concentrator (compound parabolic) must be installed on the roof of the solar tower. Thermal energy needed for operating the conventional cement plant in solar mode mainly depends on the heat losses in the solar reactor given in Eq. (3.1). Solar reactor design for a solar cement plant is as follows (Meier et al., 2006):

$$\dot{Q}_{solar} = \frac{\dot{Q}_{rxn} + \dot{Q}_l}{\eta_{SF}\alpha_{SR}} \tag{3.1}$$

Heat and mass balance for the solar reactor is shown in Fig.3.2. Please find a detailed description of heat balance for the solar reactor given. Assumptions and factors taken into consideration are as follows:

- Calcination of raw material starts within the calciner only.
- Kiln gas is thoroughly mixed with tertiary air, and no heat is lost from the mixing chamber.
- Unreacted gases and the calcined raw material must exit the solar reactor at a uniform temperature.
- Steady state equilibrium condition within the system is considered.

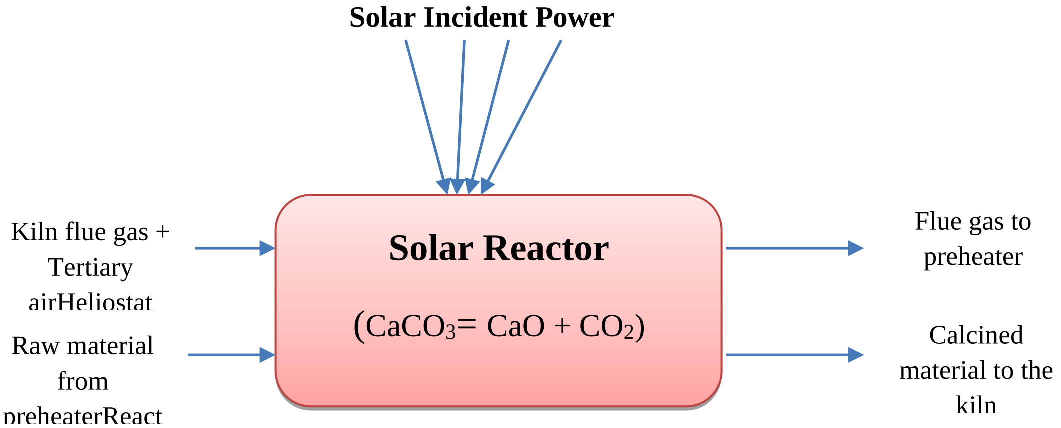


Fig.3.2 Solar reactor heat and mass balance

A solar calciner heat balance is expressed as (Gonzalez and Flamant, 2013):

$$\dot{Q}_{rxn} + \dot{Q}_{hrm} = \dot{Q}_{Ta} + \dot{Q}_{Kg} + \dot{Q}_{SR,th} \tag{3.2}$$

$$\dot{Q}_{SR} = \frac{\dot{Q}_{SR,th}}{\eta_{th}} \tag{3.3}$$

It is assumed that the tertiary air and the kiln gas mix ideally and leave the solar calciner at a common temperature $T_{out.gas}$.

$$\dot{Q}_{Ta/Kg} = \dot{m}_{\frac{Ta}{Kg}} C_{p,\frac{Ta}{Kg}} \left(T_{in,\frac{Ta}{Kg}} - T_{out.gas} \right) \tag{3.4}$$

Energy required to heat raw material from the inlet to the reaction temperature is given by:

$$\dot{Q}_{hrm} = \dot{m}_{rm}(1 - Rd)(1 - \%Hum)C_{p,rm}\left(T_{Calcin} - T_{in,rm}\right) \tag{3.5}$$

Energy flux required for raw material calcination is given by (Gonzalez and Flamant, 2014):

$$\dot{Q}_{rxn} = \dot{m}_{rm}\%CaO_{rm}\%Lm_{rm}(1 - Rd)(1 - \%Hum)\Delta H_{rxn}^{calc} \tag{3.6}$$

Data required for the calculation of energy required for increasing the raw material temperature to reaction temperature and for raw material calcination is shown in Table 3.1. The energy (heat) required for the calcination stage is considered as 3182 kJ/kgCaO.

Table 3.1 Data used for heat and mass balance calculation (Gonzalez and Flamant, 2013)

Data	**Value**
Ambient temperature	36℃
Atmospheric pressure	101.7 KPa
$CaCO_3$ decarbonation heat of reaction	3182 kJ/kgCaO
LHV of calciner fuel	27,867 kJ/kg
$\%\boldsymbol{CaO_{rm}}$	42
$\%\boldsymbol{Lm_{rm}}$	94
Rd	12%
Raw material feed rate	215 ton/hr
$\%\boldsymbol{Hum}$	0.1
Tertiary air volumetric flow rate	72,207Nm^3 /h
Kiln gases volumetric flow rate	13,9793 Nm^3 /h
Calciner gases volumetric flow rate	20,9690 Nm^3 /h
Raw material temperature	785℃
$\boldsymbol{T_{in,Ta}}$	851℃
$\boldsymbol{T_{in,Kg}}$	900℃
$\boldsymbol{T_{out.gas}}$	920℃
Calciner external diameter	6 m

Calciner length	40 m
Calciner external surface temperature	250℃

3.2.1 Thermal energy and land requirements

Solar and thermal energy needed to run the solar reactor for the calcination of raw material in cement production using a heat balance equation is as follows:

Solar incident power on the solar reactor (Gonzalez and Flamant, 2013):

$$\dot{Q}_{SR} = \frac{\dot{Q}_{rxn} + \dot{Q}_{hrm}}{1 - \%\dot{Q}_{l}} \tag{3.7}$$

The mirror surface needed:

$$S_{mirror} = \frac{\dot{Q}_{SR}}{\eta_{SF} DNI} \tag{3.8}$$

Solar field optical efficiency is given as:

$$\eta_{SF} = \rho_{mr} shcos_{ef} Atm_{ab} SP_{reac} H_{av} \alpha_{reac} \tag{3.9}$$

The required number of heliostats:

$$N_{helio} = \frac{S_{mirror}}{S_{helio}} \tag{3.10}$$

Energy flux reaching the solar field from the sun:

$$\dot{Q}_{sef} = \frac{\dot{Q}_{SR}}{\eta_{SF}} \tag{3.11}$$

Process's overall efficiency:

$$\eta_{eff} = \frac{\dot{Q}_{rxn} + \dot{Q}_{hrm}}{\dot{Q}_{sef}} \tag{3.12}$$

Solar reactor power output, the required mirror surface, number of heliostats, and process efficiency can be calculated using the data shown in Table 3.2. Land surface required for the heliostat field setup was calculated based on 20% of the total land needed (Trieb, 2009). Land surface was considered for three heat loss scenarios, i.e., 15%, 30% and 45%.

Table 3.2 Parameters used for solar cement plant calculation

Parameter	**Value**
Heliostat mirror reflectivity	94%
Shadowing and blocking	2%
Cos effect	95%
Atmospheric absorption	3%
Spillage on the receiver	2%
Heliostat field availability	95%
Material absorptivity	95%
Optical solar field efficiency	79%
DNI	438 W/m^2
Heliostat surface	150 m^2

3.2.2 Maximum CO$_2$ reduction potential

The most significant amount of CO$_2$ reduction is possible if all of the thermal energy used for the calcination process is replaced with solar energy. In this case, the maximum CO$_2$ reduction equals (Moumin et al., 2020):

$$(\dot{m}_{co_2})_{max.red} = (\dot{m}_{co_2})_{conv} - (\dot{m}_{co_2})_{solmin.} \tag{3.13}$$

The minimal CO$_2$ emissions $(\dot{m}_{co_2})_{solmin.}$ from a solar cement process is determined by the raw material's CO$_2$ concentration $(Y_{rm})co_2$ and the quantity of coal used in the rotary kiln $(\dot{m}_{coal}\ )_{kiln}$(Voldsund et al., 2019):

$$(\dot{m}_{co_2})_{solmin.} = (Y_{rm})co_2\, \dot{m}_{rm} + (\dot{m}_{coal}\ )_{kiln} LHV_{coal} C_{co_2} \tag{3.14}$$

In the conventional process, the amount of CO2 emitted $(\dot{m}_{co_2})_{conv}$is calculated by raw material's CO2 concentration and the amount of coal utilized in the calciner and rotating kiln $(\dot{m}_{coal})_{calci}$:

$$(\dot{m}_{co_2})_{conv} = (Y_{rm})co_2\,\dot{m}_{rm} + (\dot{m}_{coal})_{kiln}LHV_{coal}C_{co_2} + (\dot{m}_{coal})_{calci}LHV_{coal}C_{co_2} \quad (3.15)$$

Therefore, the decrease in CO2 emissions caused by implementing the solar calciner in a conventional cement plant is computed using the amount of fuel (coal) saved (Gardarsdottir et al., 2019).

$$(\dot{m}_{co_2})_{max.red} = (\dot{m}_{coal})_{calci} \times LHV_{coal} \times C_{co_2} \quad (3.16)$$

Table 3.3 Data used for CO2 mitigation potential

Parameter	Value	Unit	References
C_{co_2}	9.465×10^{-5}	kg/kJ	(Voldsund et al., 2019)
LHV_{coal}	27,150	kJ/kg	(Gardarsdottir et al., 2019)
$(\dot{m}_{coal})_{calci}$	2.4	kg/s	(Gardarsdottir et al., 2019)
$(\dot{m}_{coal})_{kiln}$	1469	kg/s	(Voldsund et al., 2019)
$(Y_{rm})co_2$	0.3474	-	(Voldsund et al., 2019)
$\dot{m}_{rm} / \dot{m}_{clinker}$	1.6	-	(Voldsund et al., 2019)
$\dot{m}_{clinker}$	34.72	kg/s	(Voldsund et al., 2019)

Data used for the CO2 mitigation potential calculation is shown in Table 3.3. Based on the above equations, the conventional case's CO2 emissions are to be estimated as $(m_{co_2})conv/m_{clinker} = 842\ kgCO_2/t_{clinker}$. Calcination process is responsible for around 66% of these emissions. Out of the remaining 34% of emissions, 13% is due to the fuel used in the clinkering, and 21% is due to the fuel used in the conventional calciner (Markewitz et al., 2019; De Lena et al., 2019). By using a solar calciner, the CO2 emissions could be reduced to a minimum of 665 kg per tonne of clinker i.e., $(m_{co_2})solmin/m_{clinker} = 665\ kgCO_2/t_{clinker}$. Hence, the maximum 21% of the total CO_2 emission can be avoided when 100% of the calciner thermal energy required is replaced by solar energy. Remarkably, the amount of CO_2 emissions produced due to the calcination process is nearly three times greater than those caused by the usage of fossil fuels. Therefore, if CO_2 from the solar calciner is separated in a controlled manner, the impact would grow by a factor of four to 87%.

3.2.3 Heliostat field layout

Utilizing NREL's tool SolarPILOT (Solar Power Tower Integrated Layout and Optimization Tool), the heliostat field configuration is created based on the solar incident power required for the solar cement factory to operate continuously. SolarPILOT is a tool for generating and characterizing power tower (central receiver) systems. This software tool provides many essential features, which include:

Design heliostat fields by considering several factors like solar DNI, plant location, receiver geometry, heliostat configuration, tower height, market pricing, etc.

- Model several heliostat optical designs, such as those with many facets and canting or targeting techniques.
- Develop designs with multiple heliostat or receiver shapes.
- Employing intelligent aiming techniques, simulate receiver flux profiles at any given time or sun location.
- Analyze the sensitivity to a design parameter by performing parametric simulations.
- Minimize expected energy costs by optimizing the heliostat field layout and receiver dimensions.
- With an interactive plotting tool, analyze field designs, flux plotting, and aim-point plots.

A detailed explanation of SolarPILOT can be found in the literature (Meyer and Schwandt, 2017). Fig.3.3 shows an example of how SolarPILOT configures heliostat fields.

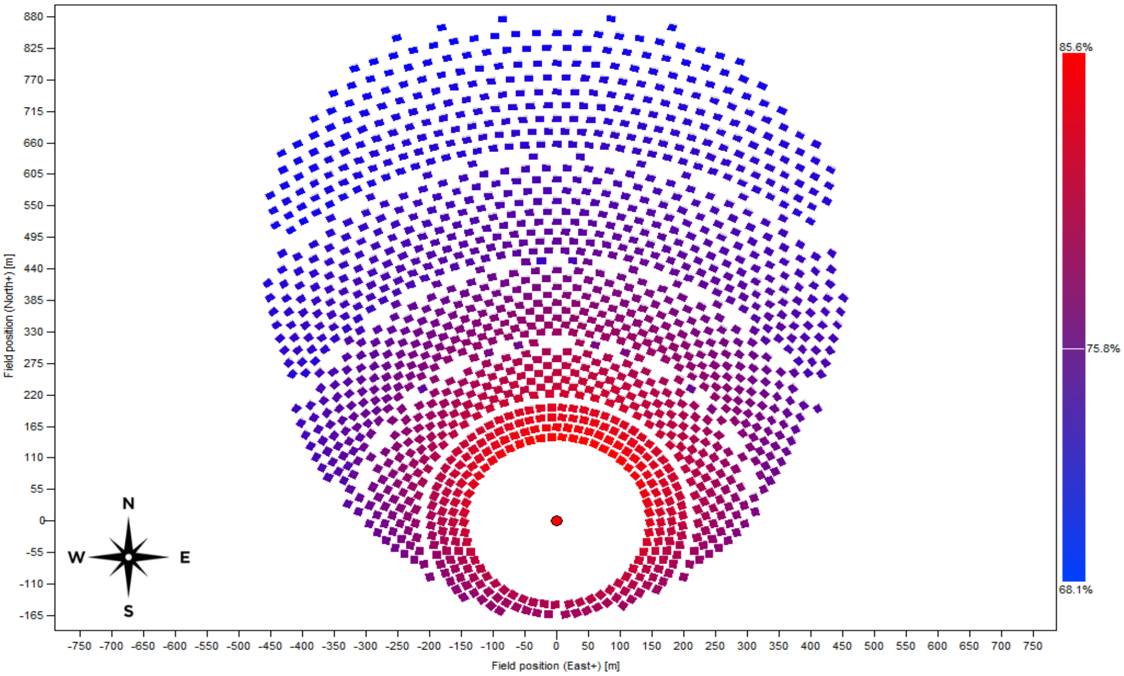


Fig. 3.3 Layout of 100 MW heliostat field at Solar PILOT

3.2.4 Location and DNI availability of the investigated plant

A conventional cement plant (Kotputli Cement Works (KCW), an UltraTech Cement Limited manufacturing unit) at *Kotputli*, Jaipur, Rajasthan, was investigated for solar thermal application. According to the Indian Minerals Yearbook 2020, the plant produced 2.37 million tons, while its production capacity is 4 million tons. Rajasthan is an ideal location for generating solar energy due to its massive amounts of unused land and constant sunlight. Having emerged as the country's solar hub after developing 10 GW solar power capacity, Rajasthan is attracting new renewable energy investments. A memorandum of understanding was signed between Coal India Limited and Rajasthan Vidyut Utpadan Nigam (RVUN) for setting up a 1,190 MW solar power project.

Local Direct Normal Irradiation (DNI) data obtained using Mateonorm 8 software determines the amount of solar energy available at the plant location. A production time of 9 hours is anticipated, with 1.5 hours required for heating up and cooling down the solar reactor. This is based on the assumption that there are almost 12 hours of sunshine each day at the site throughout the year.

Average DNI value for the plant location over 2020 was taken as the design value for the solar reactor. In addition, Table 3.4 shows the solar data like global horizontal irradiance (GHI), direct normal irradiation (DNI), diffuse horizontal irradiation (DHI), wind speed, etc. for the selected plant site, taken from the Meteonorm 8 Software (Version 8.04.21990). Monthly GHI and DHI values for 2020 at plant location are shown in Fig. 3.4. Minimum and maximum day temperature and sunshine duration at plant location for each month are shown in Fig.3.5 and Fig.3.6, respectively.

Table 3.4 Solar data at the plant site

Month	**H_Gh** (kWh/m^2)	**H_Bn** (kWh/m^2)	**H_Dh** (kWh/m^2)	**T_a** (°C)	**T_d** (°C)	**RH** (%)	**p** (hPa)	**FF** (m/s)
January	117	150	40	15.2	5.9	54	970	1.5
February	134	158	43	19.2	6.3	43	971	1.9
March	181	189	59	25.2	6.8	31	972	2.1
April	192	159	79	30.6	7.5	24	972	2.4
May	199	143	93	34.1	11.9	26	973	3.0
June	175	91	104	33.4	19.1	43	973	3.1
July	154	73	100	30.0	23.9	70	972	2.8
August	147	77	91	28.6	24.1	77	972	2.5
September	154	133	65	28.9	20.9	62	972	2.1
October	147	138	62	27.2	13.1	42	972	1.5
November	121	139	47	21.9	9.2	44	971	1.2
December	112	147	38	16.9	6.5	50	971	1.2
Year	1834	1597	822	25.9	12.9	47	972	2.1

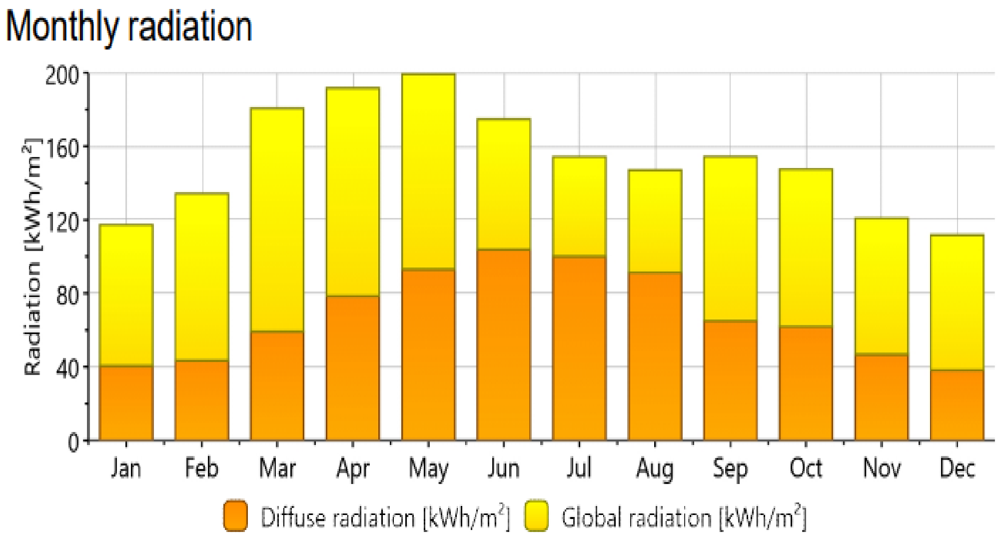


Fig.3.4 Monthly GHI and DHI at plant location

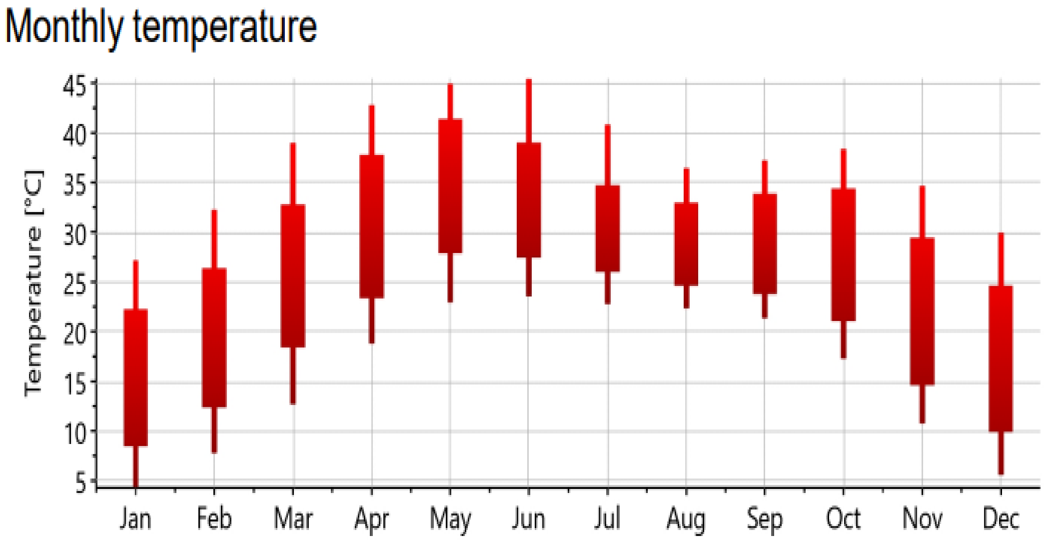


Fig.3.5 Monthly minimum and maximum day temperature at plant location

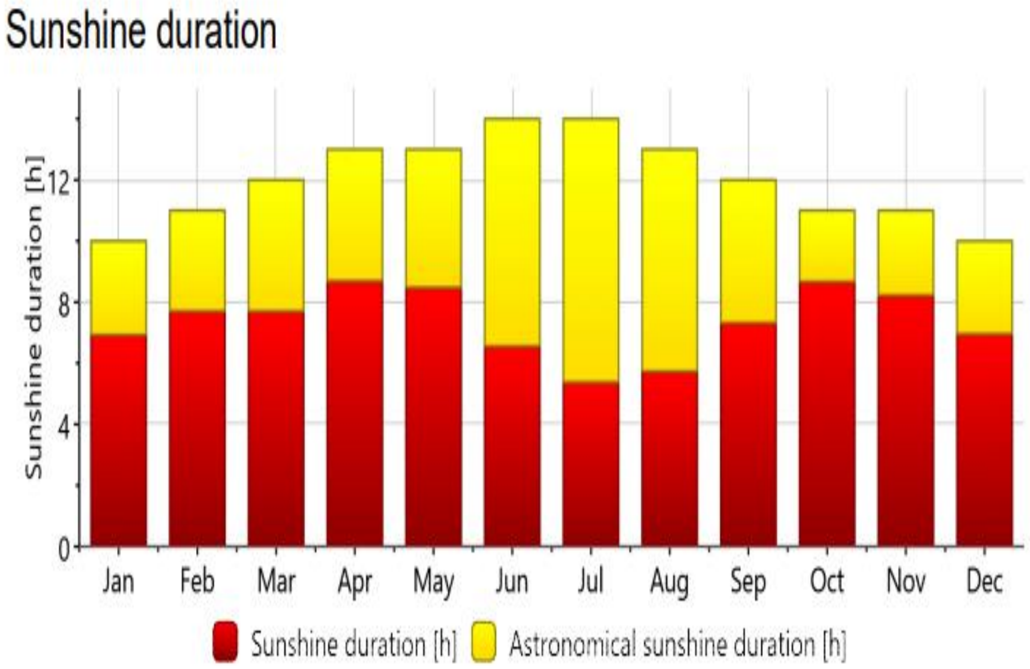


Fig.3.6 Monthly sunshine duration at plant location

3.2.5 Energy assessment and plant functioning

The concept of an energy assessment is shown in Fig.3.7. Solar field efficiency can be computed on an hourly basis for all hours of the year using the SolarPILOT tool. In addition, energy output of the solar reactor, the thermal energy storage load, and the conventional firing power can be computed at an hourly resolution together with the supplied solar DNI. As a result, it is possible to determine three significant parameters: full load hours of storage system, solarization rate of the process and CO_2 emissions reduction capability.

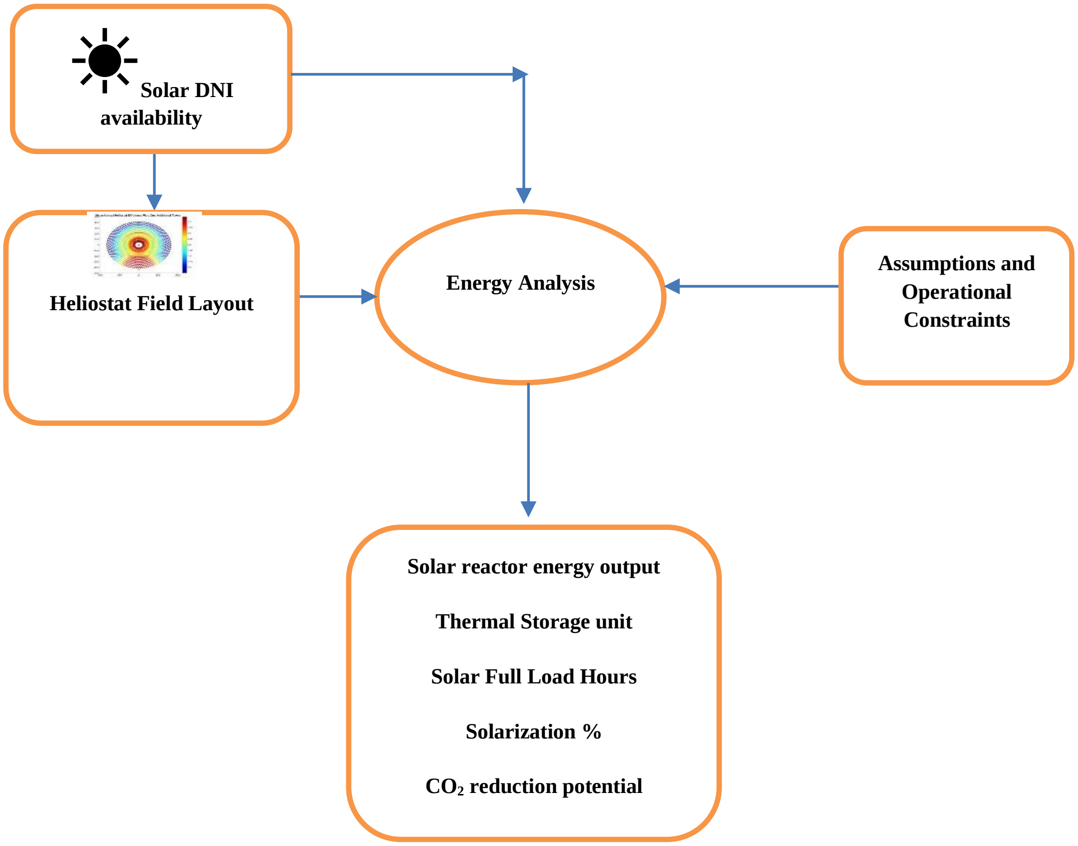


Fig.3.7 Energy assessment in the hybrid cement production process

There is no way that a solar cement plant can run continuously throughout the whole solar day. Therefore, several assumptions/constraints and modifications are considered and included in this model. The model is considered a solar calciner, constructed and tested at the German Aerospace Centre (DLR). Operational assumptions were outlined by the Aerospace Centre (Moumin et al., 2020). Assumptions and modifications considered are as follows:

i. Solar reactor needs at least two hours to warm up.

ii. No reaction takes place during the warm-up period.

iii. Solar calciner needs a minimum of 20% loading to start.

iv. If solar reactor does not produce enough calcined material required by the rotary kilns, then the thermal storage unit provides for the deficit.

v. Minimum heat loss from the calcined material in thermal storage unit.

vi. Conventional calciner starts in operating mode when the solar calciner is not able to produce enough material required by rotary kiln or there is not enough stored calcined material for further operation.

vii. Conventional calciner does not have any minimum load restriction.

viii. Solar cement plant has same efficiency as conventional cement plant regardless of load cases.

Assessment of a plant's energy can be accomplished with analytical equations and balances, which can be solved in EXCEL. Fig.3.8 shows a schematic representation of plant operation for a solar multiple of SM > 1 daily. During the initial and final hour(s) of sunshine, there isn't enough solar power to run the solar calciner, thus the calcined material is either retrieved from the thermal storage unit or created using a conventional method. Despite this, existing solar radiation is used to warm up solar reactors. Solar calciner begins to operate as soon as solar power reaches 20% of the reactor design point.

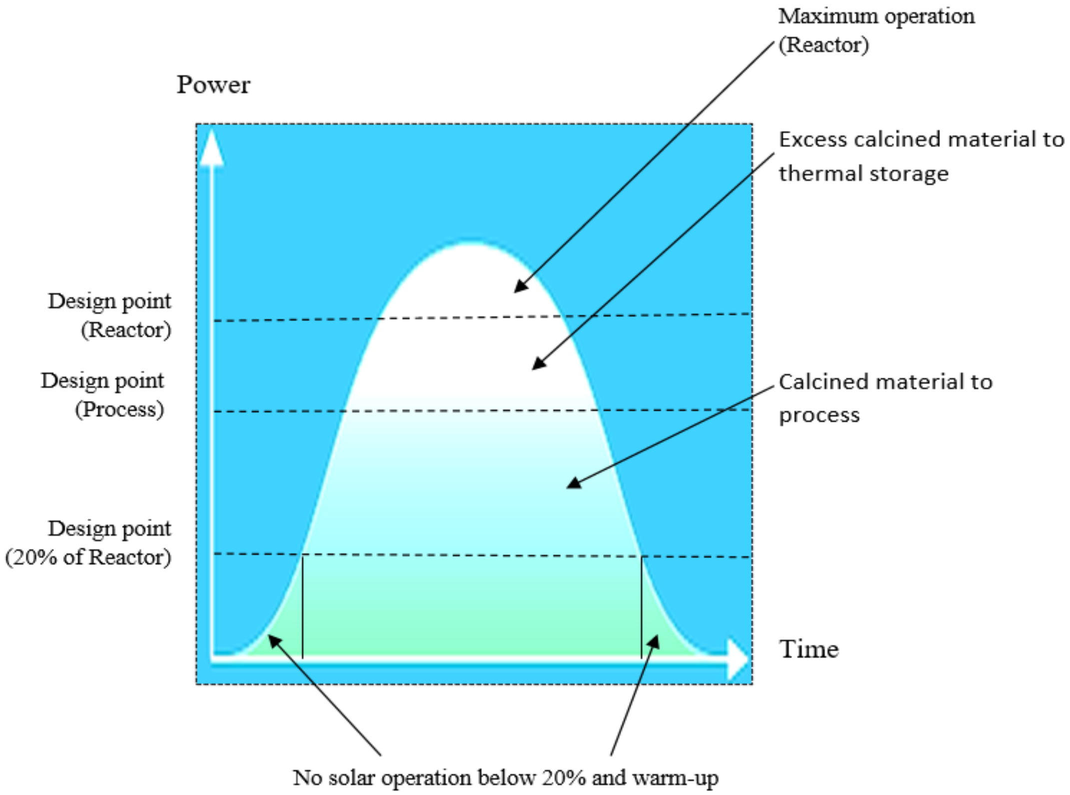


Fig.3.8 Solar cement plant operation during the day with a solar multiple (SM) > 1

Once more, the storage or conventional calciner makes up the difference between the generated calcined material and the design point. After the solar reactor achieves its optimum value, the calcined meal is immediately provided for the subsequent process. When the solar multiple is more than 1, the solar reactor produces extra material kept in thermal storage. The design point load is the maximum load that the reactor can handle. As a result, energy above the design point is not used.

Based on the heliostat field area A_{helio}, the field efficiency $\eta_{helio}(t)$ and solar DNI (t) in hourly resolution, the solar power produced as (Moumin et al., 2020):

$$\dot{Q}_{sol.\ in}(t) = A_{helio} \times \eta_{helio}(t) \times DNI(t) \tag{3.17}$$

Calciner energy output is calculated by considering its thermal efficiency and the above-mentioned limitations (Meier et al., 2006):

$$\dot{Q}_{SR.th}(t) = \eta_{th} \times \dot{Q}_{sol.\ in}(t) \tag{3.18}$$

In addition to those already discussed, there are several other cases as well:

Rate of production is more than or equal to the rate of demand

$\dot{Q}_{SR.th}(t)$>= $\dot{Q}_{demand}$, then:

$\dot{Q}_{demand}$ is immediately sent into the rotary kiln,

Surplus of raw material is transferred to the storage unit until it has achieved its design load, $\dot{Q}_{TSS}$<$\dot{Q}_{TSS,design}$:

$$\dot{Q}_{TSS.in}(t) = \dot{Q}_{SR.th}(t) - \dot{Q}_{demand} \tag{3.19}$$

$$\dot{Q}_{TSS.out}(t) = \dot{Q}_{demand} - \dot{Q}_{SR.th}(t) \tag{3.20}$$

$$\dot{Q}_{conv}(t) = \dot{Q}_{demand} - \dot{Q}_{SR.th}(t) - \dot{Q}_{TSS.out}(t) \tag{3.21}$$

Additionally, no further raw material is generated in the calciner if the thermal storage is filled $\dot{Q}_{TSS} = \dot{Q}_{TSS.design}$

Difference between the solar calciner output and the input of the rotary kiln ($\dot{Q}_{SR.th}(t) < \dot{Q}_{demand}$), filled by the thermal storage unit so far it is not empty $\dot{Q}_{TSS} > 0$.

Conventional, fossil-fired calciner starts operating when there is no calcined material in the thermal storage $\dot{Q}_{TSS} = 0$, or the requirement is more than the stored material $\dot{Q}_{TSS.out}(t) < \dot{Q}_{SR.th}(t) - \dot{Q}_{demand}$

All the hours in a year are summed up $\sum_{t=0}^{8000} \dot{Q}_{conv}$ to calculate the heat supplied by conventional burning $\dot{Q}_{conv}(t)$. As a result, we can determine the key performance indicators of our energy analysis:

Total time operation using fossil fuel:

$$t_{fossil} = \frac{\sum_{t=0}^{8000} \dot{Q}_{conv}}{\dot{Q}_{conv.full}} \tag{3.22}$$

Total time operation using solar:

$$t_{sol} = 8000h - t_{fossil} \tag{3.23}$$

Calciner process solarization (SolR):

$$SolR = \frac{t_{sol}}{8000h} \tag{3.24}$$

Annual fuel savings:

$$\dot{Q}_{Fuel.save} = \dot{Q}_{conv.full} \times t_{sol} \tag{3.25}$$

Maximum emission reduction (CO_2) determined as 21% for the cement manufacturing process is shown in section 3.3.

Based on the model, storage hours $t_{TSS}$and the thermal energy throughput $\dot{Q}_{SR.th}$of the solar reactor, the size of the thermal storage $\dot{Q}_{TSS.design}$ is calculated as follows:

$$\dot{Q}_{TSS.design} = \dot{Q}_{SR.th} \times t_{TSS} \tag{3.26}$$

Thermal storage size is assessed using optimization techniques. Conventional firing full load $\dot{Q}_{conv.full}$ is evaluated as (Moumin et al., 2020):

$$\dot{Q}_{conv.full} = \dot{m}_{coal.calcin} \times LHV_{coal} \tag{3.27}$$

3.2.6 Economic analysis

Economic analysis and energy analysis are closely related to each other. Concept for the economic analysis is based on Eq. 3.1 which explains the direct relation between thermal losses and solar reactor efficiency. Economic feasibility of the model is determined through the payback time (PBT) and the internal rate of return (IRR) criteria.

Major components of the concentrating solar system are heliostats, central tower, a solar reactor and a compound parabolic concentrator. A thermal storage unit is also another significant component as the process is operated in hybrid mode. Solar field operates for nine hours a day in order to produce the calcined material that is used for the online process, as well as for the remaining fifteen hours of the day. Fossil (coal) energy to be replaced with solar energy is considered from 50% to 100 %. Thermal losses from the solar reactor are considered to be 15%, 30%, and 45% respectively. Complete specifications of the solar cement plant are given in Table 3.5.

Table 3.5 Technical specifications for a solar-powered cement plant

Parameter	**Value**	**Reference**
Fossil energy to be replaced (%)	100; 90; 80; 70; 60;50	Present study
Thermal losses (%)	45; 30; 15	Present study
Specific heat	3182 kJ/kg of CaO	(Badie et al., 1980)
Amount of limestone in raw material (%)	94	UltraTech Cement Plant, *Kotputli*
CaO concentration in limestone (%)	42	UltraTech Cement Plant, *Kotputli*
Working days annually	365 (24 hrs/ day)	UltraTech Cement Plant, *Kotputli*
Clinker production rates	6500 (Tons/day)	UltraTech Cement Plant, *Kotputli*
Plant location DNI (W/m^2)	438	Meteonorm 8 Software

Direct investment cost includes the cost of heliostat field, the land, reinforcement of the existing preheater tower, solar reactor, CPC and storage unit. Costs used are taken from solar tower CSP technology until 2025 and costs are adjusted to ₹ using an exchange rate of 1EUR = ₹90 (Dieckmann et al., 2017).

Investment cost for the heliostat field include mirror modules, structure, drives, control and wired connection, installation and checking. Investment costs for the tower include expenditures for strengthening the existing preheater tower. Investment cost for the thermal storage system includes one storage tank, pump and heat exchanger. There is no need for storage medium. Pump and heat exchanger costs are two times the normal cost due to high operating temperature (Gonzalez and Flamant, 2013).

There is no reliable cost data available for the solar reactor because only lab size reactors have been developed till now. Solar calciners will resemble fossil fuel rotary kiln calciner with no firing equipment. Therefore, the solar calciner cost is 30% less than the fossil fuel calciners (Garrett, 2012)**.** CPC costs are calculated from the literature, based on a MW solar incident (Meier et al., 2006; Gonzalez and Flamant, 2013).

Specific investment expenses and equations used in capital expenditure or CAPEX calculation are shown in Table 3.6 and 3.7. Operational expenditure or OPEX cost includes operation and management cost and the fuel savings cost, which is shown in Table 3.8 and Table 3.9. All other costs like transportation cost for calcined material and additional electricity expenses are neglected in this analysis.

Table 3.6 Specific investment costs of components for CAPEX calculation

Component	Symbol	Value	Unit	References
Heliostat Field	k_{HF}	8100	₹/m^2	(Von Storch, 2016)
Tower	k_{Tow}	5679540	₹/m	(Von Storch, 2016)
Solar Calciner	k_{Calc}	36509850	₹	(Garrett, 2012)
Reference Calciner Thermal Power	p_{Calc}^{ref}	293	kW$_{th}$	(Garrett, 2012)
CPC	k_{cpc}	2570760	₹/MW	(Meier et al., 2006)
Solar Incident Power at Tower	$p_{Tow}^{sol.in}$	$\frac{Q_{sol.in}}{No.of\ Towers}$		-
Fixed Costs CPC	I_{CPC}^{fix}	3922290	₹	(Meier et al., 2006)
TSS	k_{Tss}	786.4	₹/kW$_{th}$	(Gonzalez and Flamant, 2014; Von Storch, 2016)
Thermal Storage Size	Q_{TSS}		kW$_{th}$	-
Land	k_{Land}	135	₹/m^2	Assumption

Indirect Costs	$k_{Indirect}$	20	%	Assumption

Table 3.7 CAPEX cost calculation for solar cement plant

Name	Symbol	Equation	Eqn no.	References
Heliostat Field Costs	I_{HF}	= $k_{HF}A_{HF}$	(3.28)	-
Tower Costs	I_{Tow}	= $k_{Tow}H_{Tow}$	(3.29)	-
Solar Calciner Costs	I_{Calc}	= $k_{Calc}\left(\dot{Q}_{SR,th}\middle\| p^{ref}_{Calc}\right)^{0.48}$	(3.30)	(Garrett, 2012)
CPC Costs	I_{CPC}	= $k_{cpc}p^{sol.in}_{Tow} + I^{fix}_{CPC}$	(3.31)	(Meier et al., 2006; Gonzalez and Flamant, 2014)
Thermal Storage System Costs	I_{TSS}	= $k_{Tss}Q_{TSS}$	(3.32)	-
Land Costs	I_{Land}	= $k_{Land}A_{Land}$	(3.33)	-
Direct Costs	I_{Direct}	= $I_{HF} + I_{Tow} + I_{Calc} + I_{CPC} + I_{TSS}$	(3.34)	-
Indirect Costs	$I_{Indirect}$	= $k_{Indirect}I_{Direct}$	(3.35)	-
Total (CAPEX)	I_{Tot}	= $I_{Direct} + I_{Indirect} + I_{Land}$	(3.36)	-

Table 3.8 Specific investment costs for OPEX calculation

Name	Symbol	Value	Unit	References
Specific Operation & Management Costs	k_{OM}	2	%	Assumption
Specific Coal Costs	k_{coal}	8100	₹/t	Assumption

Table 3.9 OPEX cost calculation for solar cement plant

Name	Symbol	Equation	Equation No	References
O&M Costs (Annual)	K_{OM} =	$k_{OM}I_{Tot}$	(3.37)	-
Fuel Savings (Annual)	$K_{Fuel.save}$ =	$k_{coal}Q_{Fuel.save}$	(3.38)	-
Total (OPEX)	OPEX	$K_{OM} -$	(3.39)	-

=	$K_{Fuel.save}$

CO_2 avoidance cost and clinker cost are calculated by considering the yearly CO_2 avoidance and extra costs from solar calcination. Table 3.10 provides an overview of the specified expenses.

Table 3.10 CO_2 avoidance and clinker costs

Name	**Symbol**		**Equation**	**Eqn. no.**
Total Annual Costs	$K_{an,tot}$	=	$K_{OPEX} + I_{CAPEX}$	(3.40)
CO_2 Avoidance (Annual)	$m_{CO_2.av}$	=	$Q_{Fuel.save} c_{CO_2}$	(3.41)
CO_2 Avoidance Costs	$k_{CO_2.av}$	=	$\frac{K_{an,tot}}{m_{CO_2.av}}$	(3.42)
Clinker Costs	$k_{clinker}$	=	$k_{clinker,base} + \frac{K_{an,tot}}{m_{clinker.an}}$	(3.43)

A detailed estimation cost for a 6500 TPD clinker cement plant is shown in Table 3.11. Cost is estimated for 100% energy substitution with 15%, 30% and 45% thermal losses in solar reactor.

Table 3.11 Detailed cost calculation for a 6500 TPD clinker solar cement plant

		Energy substitution					
Capital costs	**% Thermal losses**	**100%**	**90%**	**80%**	**70%**	**60%**	**50%**
Heliostats (million ₹)	15%	11825.59	10643.03	9460.47	8277.91	7095.35	5912.80
	30%	14417.19	12975.47	11533.75	10092.03	8650.31	7208.60
	45%	18305.19	16474.67	14644.15	12813.63	10983.11	9152.60
Land (million ₹)	15%	985.50	886.95	788.40	689.85	591.30	492.75
	30%	1201.50	1081.35	961.20	841.05	720.90	600.75
	45%	1525.50	1372.95	1220.40	1067.85	915.30	762.75
Tower (million ₹)	15%	1306.28	1175.65	1045.02	914.40	783.77	653.14
	30%	1476.40	1328.76	1181.12	1033.48	885.84	738.20
	45%	1646.65	1481.99	1317.32	1152.66	987.99	823.33

Solar Calciner	15%	47.77	42.99	38.22	33.44	28.66	23.89
(million ₹)	30%	52.44	47.20	41.95	36.71	31.46	26.22
	45%	58.87	52.98	47.10	41.21	35.32	29.44
CPC	15%	1648.24	1483.42	1318.59	1153.77	988.94	824.12
(million ₹)	30%	2039.14	1835.23	1631.31	1427.40	1223.48	1019.57
	45%	2551.54	2296.39	2041.23	1786.08	1530.92	1275.77
TSS (million ₹)		2.14	1.93	1.71	1.50	1.28	1.07

A project's cash flow potential is significantly affected by fuel cost and CO_2 cost. Hence, a sensitivity analysis is needed to obtain the PBT and IRR of the project. CO_2 emissions factor is considered as 2.6 per ton of coal.

The data from Table 3.12 is used to carry out the sensitivity analysis and PBT and IRR are calculated through the use @RISK software.

Table 3.12 Data input for sensitivity analysis

General	**Value**	**References**
Analysis period (years)	30	-
Inflation rate	2.28%	-
Real discount rate	7.22%	-
Federal tax	35%	-
State tax	8.84%	-
Property tax	0%	-
Sales tax	0%	-
Loan (debt) percent	100%	-
Financial period (years)	30	-
Ratexv	8.50%	-
Depreciation	Value	-
Utility	Value	-
Coal price per tonxv	₹7200	Johnston et al., 2011
CO_2proce per tonxv	₹1680	DECC, 2013
Incentives	Value	-
ITC, Federal	30%	-

ITC, state	0	-

3.3 Energy conservation potential estimation

The steps taken for evaluating the potential of SIPH for Indian cement manufacturing industry (Fig.3.9) involve (a) identifying the nation's cement plants (b) finding out the annual production capacity and actual production of each plant (c) evaluating the annual thermal energy requirements for calcination process of each plant (i.e. gross SIPH potential) (d) assessing the potential for solar process heating to mitigate CO_2 emissions. The subsequent sections provide a brief explanation of each of the aforementioned steps.

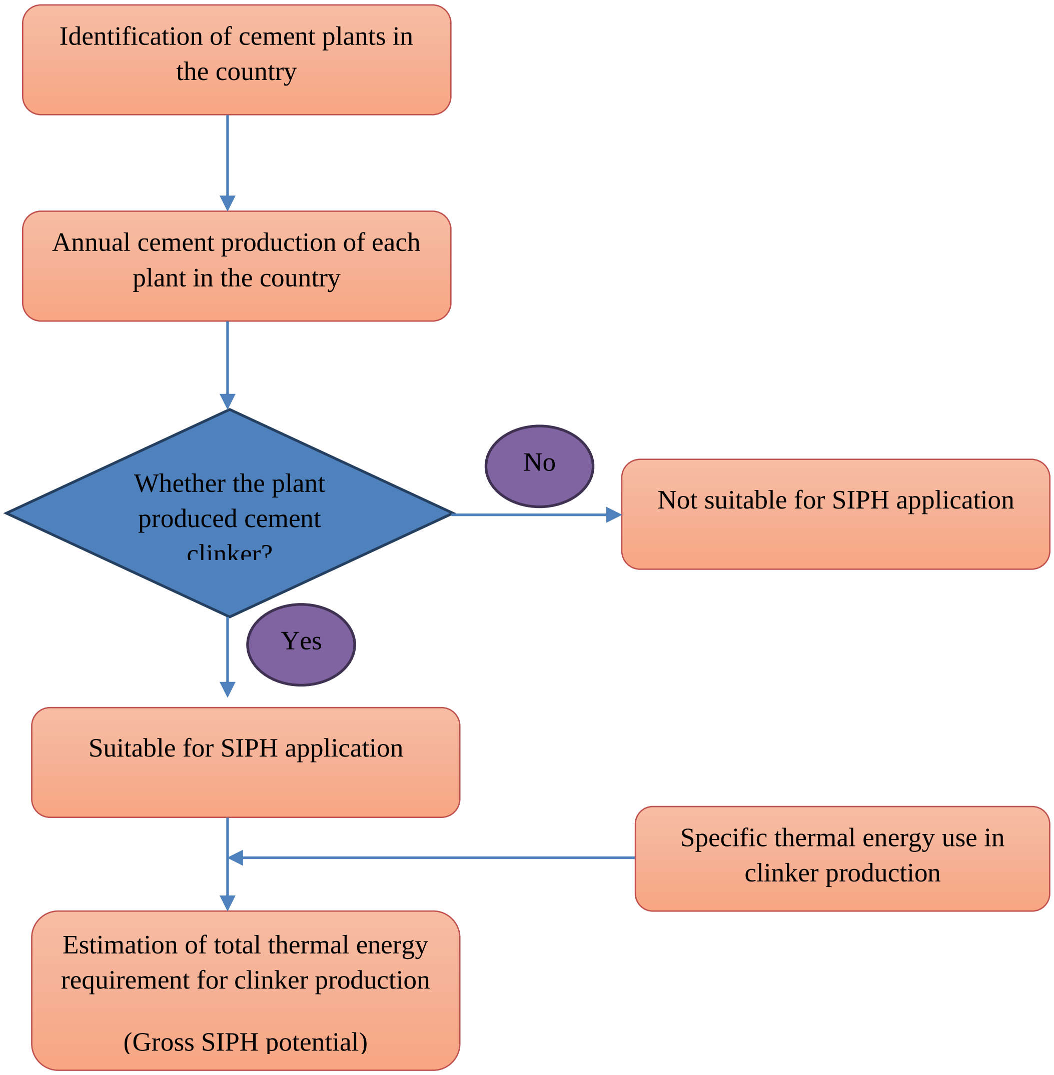


Fig.3.9 Methods used in study to estimate SIPH potential

3.3.1 Identification and characterization of cement plants across India

The location of cement plants has been identified, and data concerning each plant, like annual production capacity, actual annual production, and raw material used, has been collected using the information available in Centre Information System, Department for Promotion of Industry and Internal Trade, Government of India. Table 3.13 shows an example of cluster cement plants in Rajasthan and their installed capacity and actual production for the year 2019.

Table 3.13 Location-wise data of cement plants in Rajasthan, India [Indian Minerals Year book 2019]

Plant Name	Location	Annual Installed Capacity (In million tonnes)	Annual Actual Production (In million tonnes)	Raw material used	Whether suitable for SIPH?
ACC Ltd	Lakheri, Bundi	1.5	-	Coal	No
Ambuja Cement Ltd	Rabriyawas, Pali	3.6	2.37	Coal	Yes
Birla Corp. Ltd	Chanderia, Chittorgarh	4	3.57	Coal	Yes
Shriram Cement Works	Kota	0.4	-	Coal	No
India Cements Ltd	Banswara	1.8	1.59	Coal	Yes
J.K. Cement Ltd	Gotan White, Nagaur	0.5	-	Coal	No
J.K. Cement Ltd	Mangrol, Chittorgarh	2.5	2.56	Coal	Yes
J.K. Cement Ltd	Nimbahera, Chittorgarh	3.3	2.39	Coal	Yes

JK Lakshmi Cement Ltd	Sirohi	8.7	3.43	Coal	Yes
Lafarge Cement	Chittorgarh	2.6	2.31	Coal	Yes
Mangalam Cement I & II	Kota	3.25	2.62	Coal	Yes
Nirma Cement	Pali	2.28	1.68	Coal	Yes
Bangur Cement	Suratgarh	3.6	1.34	Coal	Yes
Beawar I & II, Unit-III Andheri Deori	Ajmer	3.6	1.74	Coal	Yes
Ras New Cement Unit	Ras	4	3.25	Coal	Yes
UltraTech Cement Ltd	Aditya, Chittorgarh	8	0.55	Coal	Yes
UltraTech Cement Ltd	Kotputli, Jaipur	4	2.83	Coal	Yes
Shree Cements	Ras, Pali	3	3.24	Coal	Yes
UltraTech Cement Ltd	Sirohi	4.85	1.73	Coal	Yes
Udaipur Cement	Udaipur	1.24	1.08	Coal	Yes
Wonder Cement	Chittorgarh	8	6.47	Coal	Yes

3.3.2 Identification of cement plants suitable for SIPH

SIPH system can be implemented at integrated and clinker cement plants through a solar calciner that uses concentrated solar energy to supply heat. Since cement grinding mills and other secondary industrial units do not use thermal energy, SIPH is not applicable.

3.3.3 Assessment of total energy required for the calcination process

The state-wise actual annual cement production (AACP) data of each cement plant (SIPH favourable) was found in the Indian Minerals Yearbook 2019 (Table 3.14). The annual thermal energy requirement (ATER) of the cement plant for the calcination process is estimated as follows:

$$\text{ATER} = (\text{AACP}) \times 0.95 \times (\text{STER}) \qquad (3.44)$$

STER is the Specific Thermal Energy Requirement (GJ/per tonne) refers to the amount of heat required to drive a calcination reaction. In this study, the value of specific thermal energy for cement production was considered 3.4GJ (in the dry process). The minimum amount of energy in the form of process heat that is required to drive the calcination reaction is 3184 kJ/kg of CaO (Vashishth and Jayant, 2021), and the clinker-to-cement ratio is considered to be 95%.

Table 3.14 India's state-wise cement plant's actual production and yearly installed capacity [Indian Minerals Year book 2019]

State/Uunion territory	**Designed capacity (MT)**	**Actual output (MT)**
Andaman Nicobar Islands	1.65	0.81
Andhra Pradesh	80.67	31.43
Assam	6.74	1.10
Bihar	10.70	3.56
Chhattisgarh	27.55	18.11
Gujarat	46.28	20.37
Haryana	7.20	1.14
Himachal Pradesh	20.39	11.48
J & K	0.83	-
Jharkhand	13.47	2.05
Karnataka	57.74	26.39
Kerala	0.86	0.40
Madhya Pradesh	46.92	20.27
Maharashtra	37.83	14.64
Meghalaya	10.14	2.28
Odisha	10.45	0
Punjab	7.45	2.63
Rajasthan	85.32	49.82
Tamil Nadu	42.99	20.25
Telangana	37.07	17.29

Uttar Pradesh	25.62	7.13
Uttarakhand	5.20	0.84
West Bengal	21.99	3.34
Total	552.25	244.02

The next chapter contains the results and discussion of the proposed systems. It presents the potential of concentrated solar energy in the Indian cement sector and the accompanying potential for CO_2 emission reduction. In addition, this section discusses the findings of solar thermal application of the investigated plant. Power required for the calcination reaction and energy out from the solar reactor was also shown. Result includes the required mirror surface, number of heliostats, land surface, solar energy flux and net efficiency of the process. All these calculations are done by assuming the thermal losses as 15, 30 and 45 percent. Further, economic feasibility of the model is determined through the payback time (PBT) and the internal rate of return (IRR) criteria.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Energy conservation and emission reduction opportunities in cement industries

The cost of cement production can be reduced by improving energy efficiency. Improvement may be attained by applying more energy-efficient techniques to the production process and the processes that support production. In cement production, there are three major steps: making raw material, clinker production, and finish grinding of clinker to produce cement powders. Raw meal preparation and clinker production can be done by wet or dry process. Most of the cement production industry uses the dry process.

4.1.1 Energy conservation and emission reduction opportunities in raw material preparation

The energy (electrical and thermal) saving and carbon dioxide (CO_2) emission reduction potential in raw material preparation through different techniques are shown in Fig.4.1. Utilization of waste heat from the rotary kiln could save a maximum quantity of electricity. It is possible to avoid 10.45 kgCO_2/tonne and 5.08 kgCO_2/tonne by using waste kiln heat and upgrading the separator/classifier, respectively. Furthermore, a maximum thermal energy of 4.3 GJ/t could be conserved through the use of gravity type silos in place of air-fluidized type silos for blending raw materials. Advanced roller mills for raw material preparation could save 0.08–0.114GJ/t thermal energy, while the electrical energy saving was 6–11.9kWh/t and emission reduction was 1.24–10.45kgCO_2/t. Conveyors play an important role in transporting raw material from one place to another and it may be available in two types i.e. Pneumatic or mechanical. With the adaptation of a mechanical type conveyor system, an estimated 3.40 kWh/ton of raw material could be saved in energy consumption, as compared to the pneumatic type of conveyor.

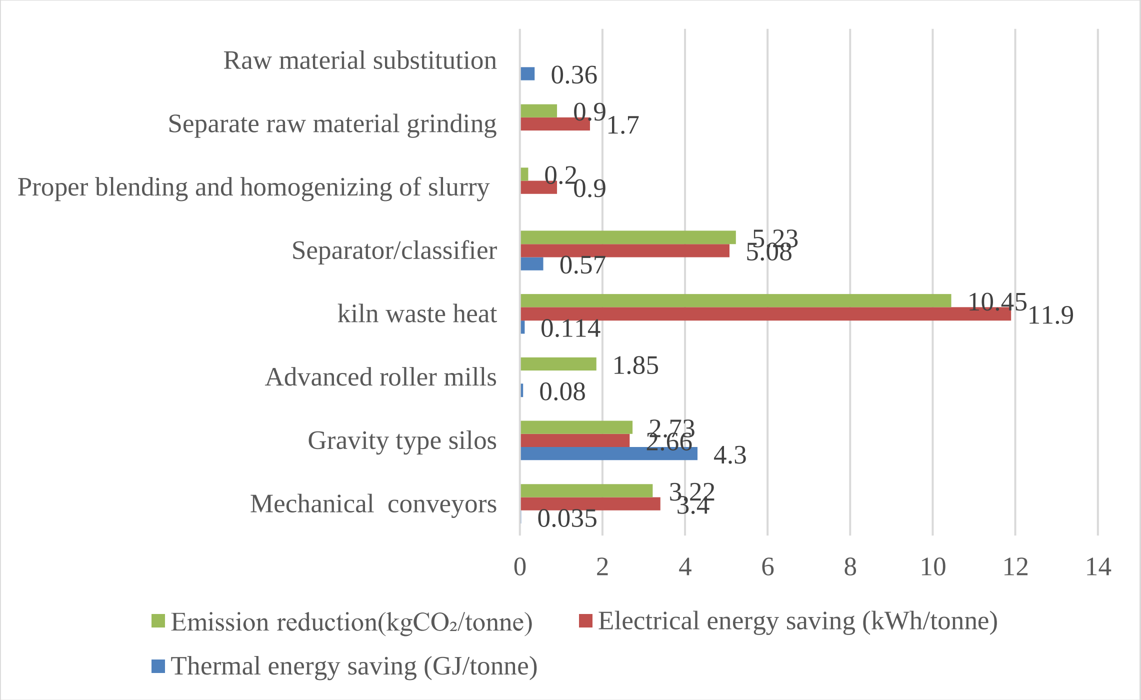


Fig.4.1 Energy saving and emission reduction through different technologies used in raw material preparation

4.1.2 Energy conservation and emission reduction opportunities in clinker production process

The summary of energy conservation opportunities and emission reduction potential in clinker production process through different technologies used is presented through a bar chart shown in Fig.4.2. The length of each bar is proportional to the value they represent. There will be a noticeable amount of thermal energy reduction as well as reduction in carbon dioxide emission if the long dry kilns are replaced with preheater/ precalciner kilns. Installation of multistage preheater and pre calciner (four or five stages) in place of one or two stage preheater used in old kilns can minimize the heat losses and improve energy efficiency of the kiln system. Furthermore, by recovering heat from the kiln shell surface, it could be feasible to boost energy efficiency and make cement manufacture more sustainable and cleaner. Twelve percent of the energy used in the rotary kiln may be saved by using infrared thermography technology.

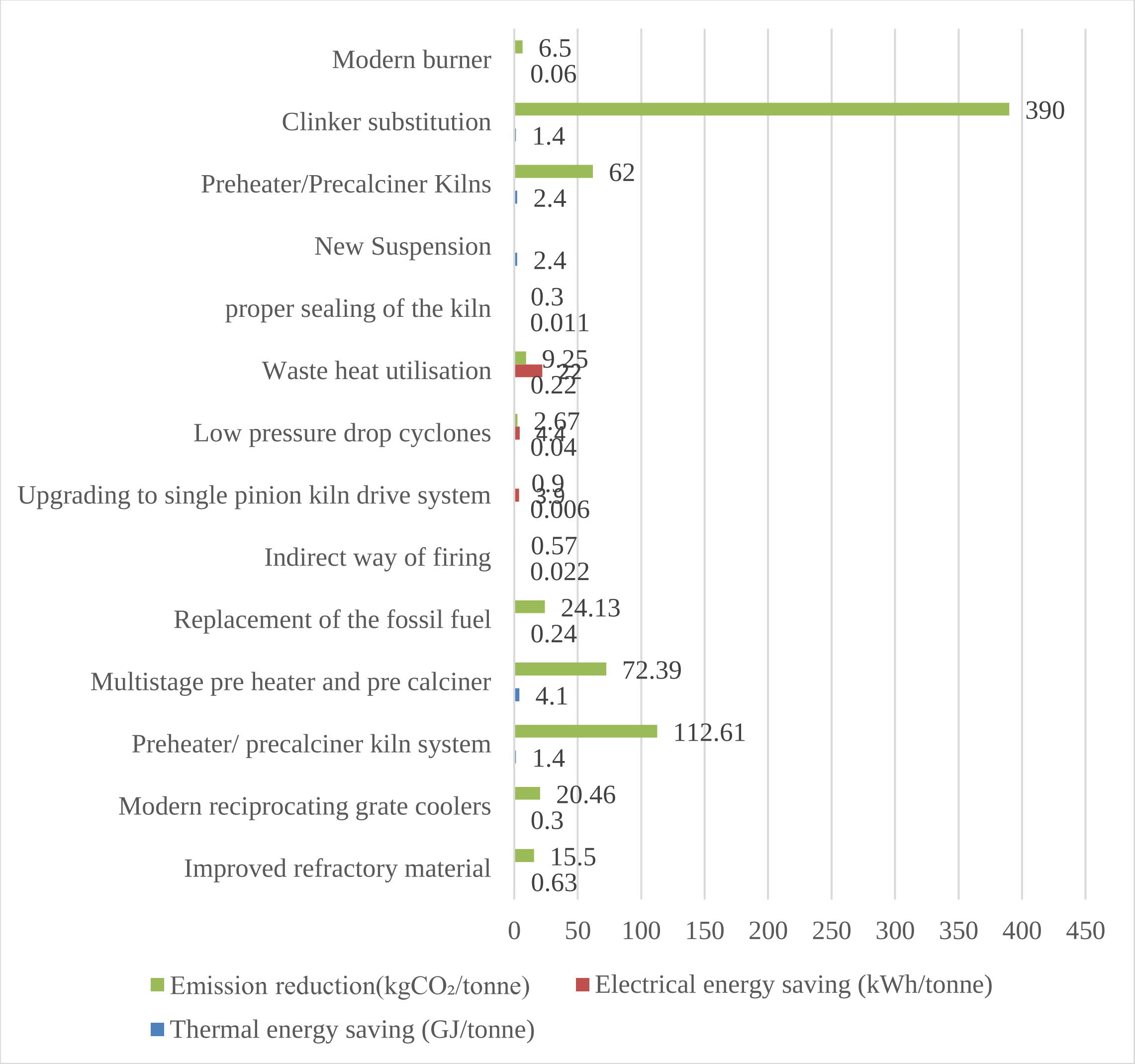


Fig.4.2 Energy saving and emission reduction through different technologies used in clinker production process

4.1.3 Energy conservation and emission reduction opportunities in cement grinding process

The possibilities for reducing carbon dioxide (CO_2) emissions and conserving energy (both thermal and electrical) during the process of cement grinding using various approaches are shown in Fig.4.3. Power consumption during the grinding process could be significantly reduced with the use of vertical type roller mills (VRM) in place of traditionally used ball type mills. Also, enhancing the cement grinding circuits could improve the energy consumption and the quality of the cement powder.

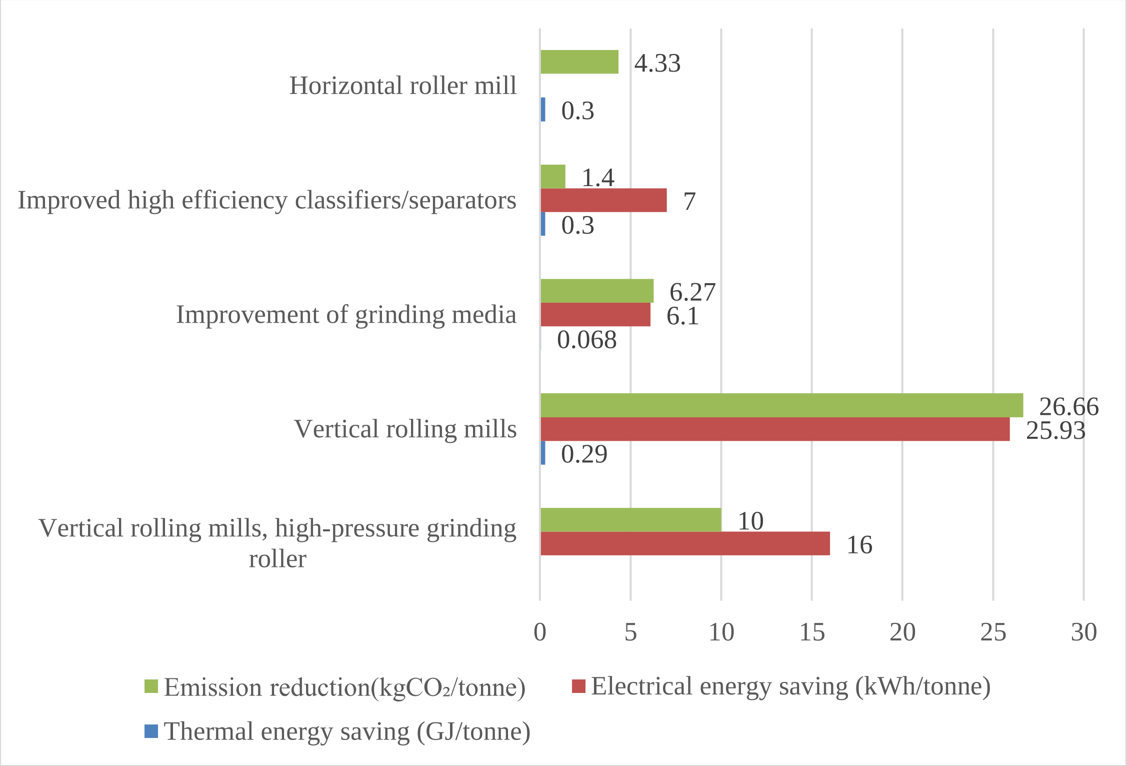


Fig.4.3 Energy saving and emission reduction through different technologies used in cement grinding process

4.2 Potential of solar thermal calciner technology for cement production in India and consequent carbon mitigation

This section presents typical results from an attempt to evaluate the potential of concentrated solar energy in the Indian cement industries and the accompanying potential for CO_2 emission reduction using the methodology described in Section 3.

4.2.1 Assessment of the solar resource available at the plant location

For each plant location suitable for SIPH applications, the solar radiation was measured in terms of Direct Normal Irradiance (DNI) and the number of cement plants that lie between a particular DNI range is shown in Fig.4.4. Result showed that there are around fifty plant locations who’s annual DNI value is greater than 1500 kWh/m^2 and sixteen plants are situated in an area with DNI value greater than 1700 kWh/m^2.

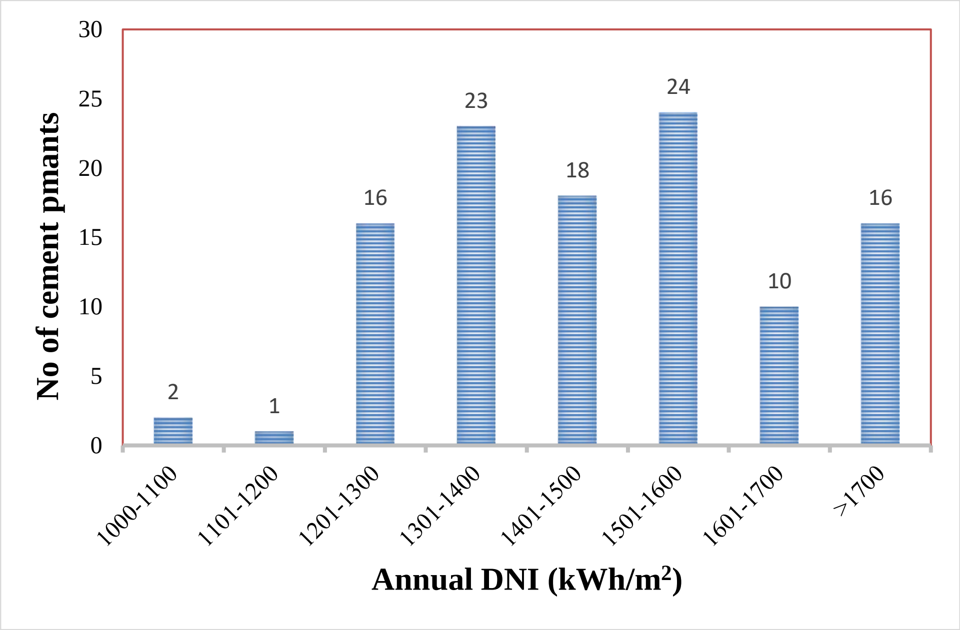


Fig.4.4 DNI of plant locations across India

4.2.2 Solar industrial process heating potential in Indian cement industries

Based on conventional and suggested (solar) systems, Table 4.1 estimates the annual thermal energy needs of clinker production for each state. An annual thermal energy of 824.71 PJ is needed for clinker production by all cement plants across India. When all the cement plants are upgraded with solar system then the annual thermal energy demand for clinker production is drastically reduced to 53.36 PJ. So, the annual thermal energy savings by the use of solar calciner reactors was found to be 771.35 PJ.

Table 4.1 Cement production and thermal energy requirement at preferred locations with clusters of cement plants in India

Indian State/UT	Annual Installed Capacity (MT)	Annual actual Production (MT)	$\mathrm{ATED_{CP}}$Based on Conventional System (PJ)	$\mathrm{ATED_{CP}}$Based on Proposed System (PJ)
Odisha	10.45	0	0	0
Jharkhand	13.47	2.05	6.62	0.42
Maharashtra	37.83	14.64	47.28	3.05
West Bengal	21.99	3.34	10.78	0.69
Himachal Pradesh	20.39	11.48	37.08	2.39
Chhattisgarh	27.55	18.11	58.49	3.78
Karnataka	32.98	15.96	51.55	3.33
Madhya Pradesh	46.92	20.27	65.47	4.23
Rajasthan	85.32	49.82	160.91	10.41
Tamil Nadu	42.99	20.25	65.40	4.23
Karnataka	24.76	10.43	33.68	2.17
Uttar Pradesh	25.62	7.13	23.02	1.49
Andhra Pradesh	80.67	31.43	101.51	6.56
Assam	6.74	1.1	3.55	0.22
Gujarat	46.28	20.37	65.79	4.25
Punjab	7.45	2.63	8.49	0.54
Uttarakhand	5.20	0.84	2.71	0.17
Meghalaya	10.14	2.28	7.36	0.47
Telangana	37.07	17.29	55.84	3.61
Bihar	10.70	3.56	11.49	0.74
Andaman Nicobar Islands	1.65	0.81	2.61	0.16
J & K	0.83	0	0	0
Haryana	7.2	1.14	3.68	0.23
Kerala	0.86	0.40	1.29	0.08
Total	605.06	255.33	824.71	53.36

Table 4.2 shows estimates of annual cement output for two threshold DNI values (1700 $\mathrm{kWh/m^2}$ annually and 1500 $\mathrm{kWh/m^2}$ annually) for the sites identified with clusters of

cement plants. These calculations have only considered the integrated and clinker cement plants. The annual thermal energy requirements have been calculated depending on the actual cement production reported by cement manufacturing industries in India.

Cement plants located in areas with annual DNI availability of 1700 kWh/m^2 or above per year generate 44.09 million tonnes of cement with a 142.41 PJ annual thermal energy need. The quantity of yearly cement output increases to 114.49 million tonnes with a corresponding annual thermal energy consumption calculated as 369.81 PJ if areas with annual DNI availability of 1500 kWh/m^2 /annum or greater are taken into consideration. It is important to note that a significant portion of cement plant clusters is found in areas with annual DNI availability of 1700 kWh/m^2 or above. Since the annual energy delivery depends on DNI availability, it is necessary to assess solar resources before installing SIPH systems.

Table 4.2 Cement production and thermal energy requirement at preferred locations with clusters of cement plants in India

DNI (kWh/m^2 /year)	**Location of cement plant**	**Annual cement production (In million tonnes)**	**Thermal energy requirement per year based on (PJ/annum)**	
			Existing system	**Proposed system**
> 1700	J.K. Cement Ltd Muddapur, Bagalkot, Karnataka	1.86	6.00	0.38
	Lafarge Cement Chittorgarh, Chittorgarh, Rajasthan	2.31	7.46	0.47
	J.K. Cement Ltd Mangrol, Chittorgarh, Rajasthan	2.56	8.26	0.52
	J.K. Cement Ltd Nimbahera, Chittorgarh, Rajasthan	2.39	7.71	0.49
	Nirma Cement, Pali, Rajasthan	1.68	5.42	0.34

	UltraTech Cement Ltd Aditya, Chittorgarh, Rajasthan	0.55	1.77	0.11
	UltraTech Cement Ltd Vikram, Neemuch, Madhya Pradesh	2.66	8.59	0.54
	Ambuja Cement Ltd Rabriyawas, Pali, Rajasthan	2.37	7.65	0.48
	Birla Corp. Ltd Chanderia, Chittorgarh, Rajasthan	3.57	11.53	0.73
	Beawar I & II, Ajmer, Rajasthan Unit-III Andheri Deori	1.74	5.62	0.35
	Shree Cements Ras, Pali, Rajasthan	3.24	10.46	0.66
	Ras New Cement Unit, Ras Rajasthan	3.25	10.49	0.66
	UltraTech Cement Ltd Sirohi, Sirohi, Rajasthan	1.73	5.58	0.35
	Wonder Cement, Chittorgarh, Rajasthan	6.47	20.89	1.33
	Udaipur Cement, Udaipur, Rajasthan	1.08	3.48	0.22
	Bharathi Cement Kadapa, Kadapa, Andhra Pradesh	3.2	10.34	0.66
	JK Lakshmi Cement Ltd Sirohi, Sirohi, Rajasthan	3.43	11.07	0.70
	Total	44.09	142.41	9.05
1500-1700	Maihar Cement I & II, Satna, Madhya Pradesh	3.88	12.53	0.79
	KJS Cement, Satna, Madhya Pradesh	1.85	5.98	0.38
	Ambuja Cement Ltd Darlaghat, Solan, Solan, Himachal Pradesh	0.86	2.78	0.17

Chettinad Cement Kallur, Gulbarga, Karnataka	1.7	5.49	0.35
Shree Digvijay Cement Co.	1.05	3.39	0.21
Sri JayaJothi Cement Plant, Kurnool, Andhra Pradesh	2.29	7.39	0.47
India Cements Ltd Malkapur, Rangareddy, Telangana	1.89	6.10	0.38
Orient Cement Chittapur, Gulbarga, Karnataka	2.29	7.39	0.47
Kesoram Industries Vasvadatta Cement, Gulbarga, Karnataka	5.3	17.12	1.08
UltraTech Cement Ltd Sewagram, Kachchh, Gujarat	2.49	8.04	0.51
Penna Cement Industries Ltd Talaricheruvu, Anantapur, Andhra Pradesh	1.18	3.81	0.24
BMM Cement, Anantapur, Andhra Pradesh	0.83	2.68	0.17
UltraTech Cement Ltd Kotputli, Jaipur, Rajasthan	2.83	9.14	0.58
UltraTech Cement Ltd Jafrabad, Amreli, Gujarat	1.17	3.78	0.24
Dalmia Cement (Bharat) Ltd Belagavi, Belagavi, Karnataka	1.55	5.01	0.32
Saurashtra Cement, Porbandar, Gujarat	1.49	4.81	0.30
Bangur Cement, Suratgarh, Rajasthan	1.34	4.33	0.27

Kalburgi Cement Gulbarga, Gulbarga, Karnataka	2.72	8.78	0.56
ACC Ltd Wadi & Wadi New, Wadi, Karnataka	3.63	11.72	0.74
Tata Chemicals Cement Division, Mithapur, Gujarat	0.5	1.62	0.10
ACC Ltd Gagal-I & II, Bilaspur, Himachal Pradesh	3.35	10.82	0.68
Kesoram Cement, Karimnagar, Telangana	1.05	3.39	0.21
Gujarat Cement Works, Amreli, Gujarat	5.3	17.12	1.08
India Cements Ltd Trinetra Cement, Banswara, Rajasthan	1.59	5.13	0.32
UltraTech Cement Ltd Hotgi, Solapur, Maharashtra	2.41	7.78	0.49
Rain Cements Ltd Kurnool Cem. Plant, Kurnool, Andhra Pradesh	1.47	4.74	0.30
UltraTech Cement Ltd Baga, Solan, Himachal Pradesh	0.86	2.78	0.17
JSW Cement Nandyal, Kurnool, Andhra Pradesh	1.76	5.68	0.36
Anantapur, Anantpur, Andhra Pradesh Cement Works	4.16	13.43	0.85
Mangalam Cement I & II, Kota, Rajasthan	2.62	8.46	0.54
Ambujanagar I & II, Kodinar, Junagadh, Gujarat	4.99	16.12	1.02

Total	70.4	227.39	14.45

4.2.3 CO_2 emission reduction potential in Indian cement industries

This section showed the quantity of CO_2 emissions that can be mitigated by installing solar industrial process heating systems in clusters of cement plants in India. The conventional cement plants (DNI >1700 kWh/m^2 /annum) with existing thermal energy produce 35267.59 thousand tonnes of CO_2 per annum, whereas the use of SIPH system in conventional cement plants reduces the CO_2 emission to 27853.86 thousand tonnes per annum shown in Fig.4.5.

Furthermore, the estimated quantity of CO_2 emissions that can be mitigated by installing solar industrial process heating systems in clusters of cement plants in India has been shown in Fig.4.6. The conventional cement plants with existing thermal energy produce 21.498 MT of CO_2 per annum whereas the use of SIPH system in conventional cement plants reduces the CO_2 emission to 16.979 MT per annum. As a result, the potential for reducing CO_2 emissions annually is relatively greater. Additionally, 100% replacement of fossil fuel with concentrated solar energy could save 45.193 MT of CO_2 emission annually (Fig.4.5). Additionally, the annual CO_2 reduction potential with the use of SIPH for different states has been shown in Fig.4.7.

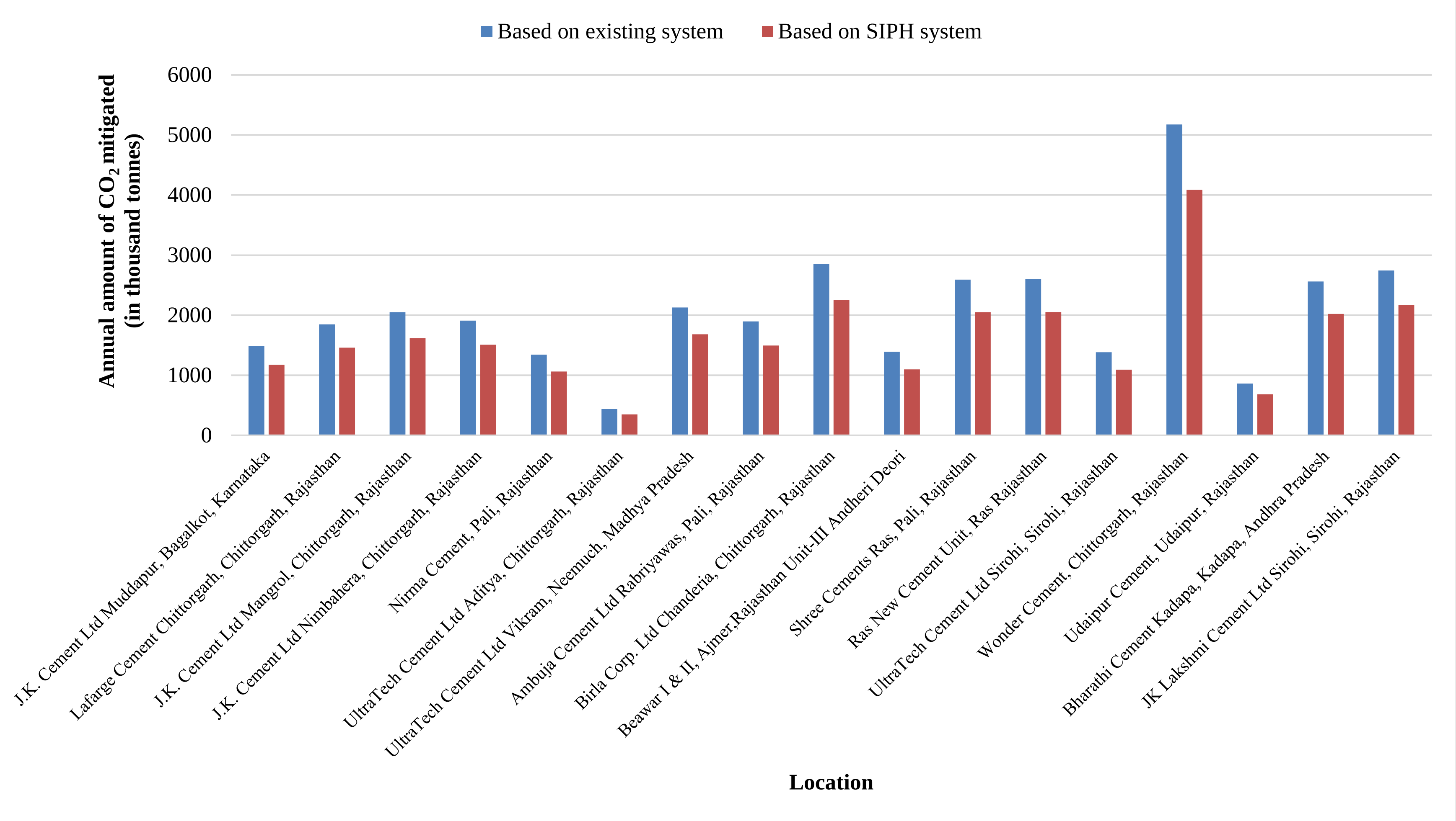


Fig.4.5 Potential of SIPH system to reduce CO_2 emissions at preferred cement plant locations (DNI > 1700 kWh/m^2/year)

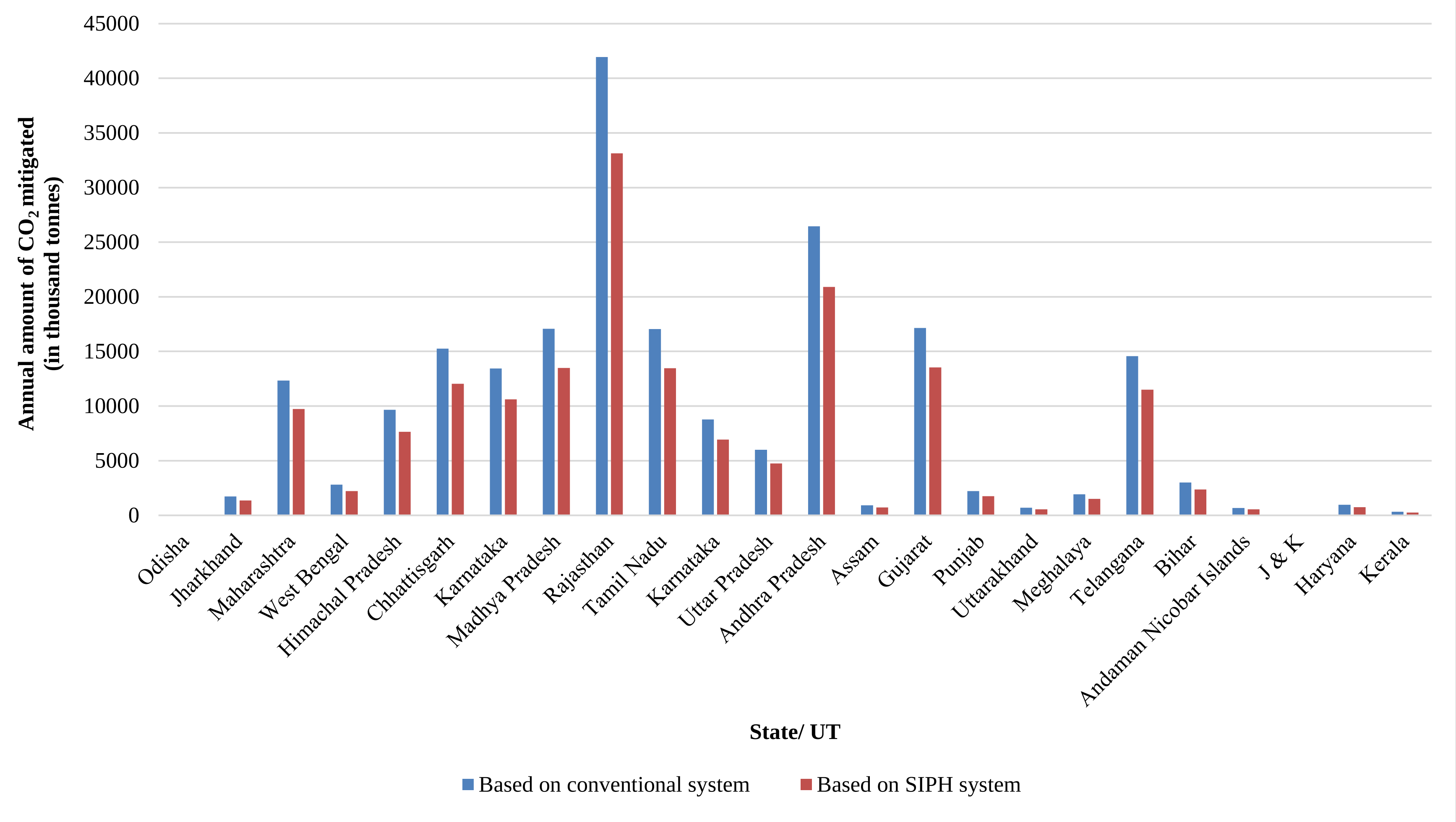
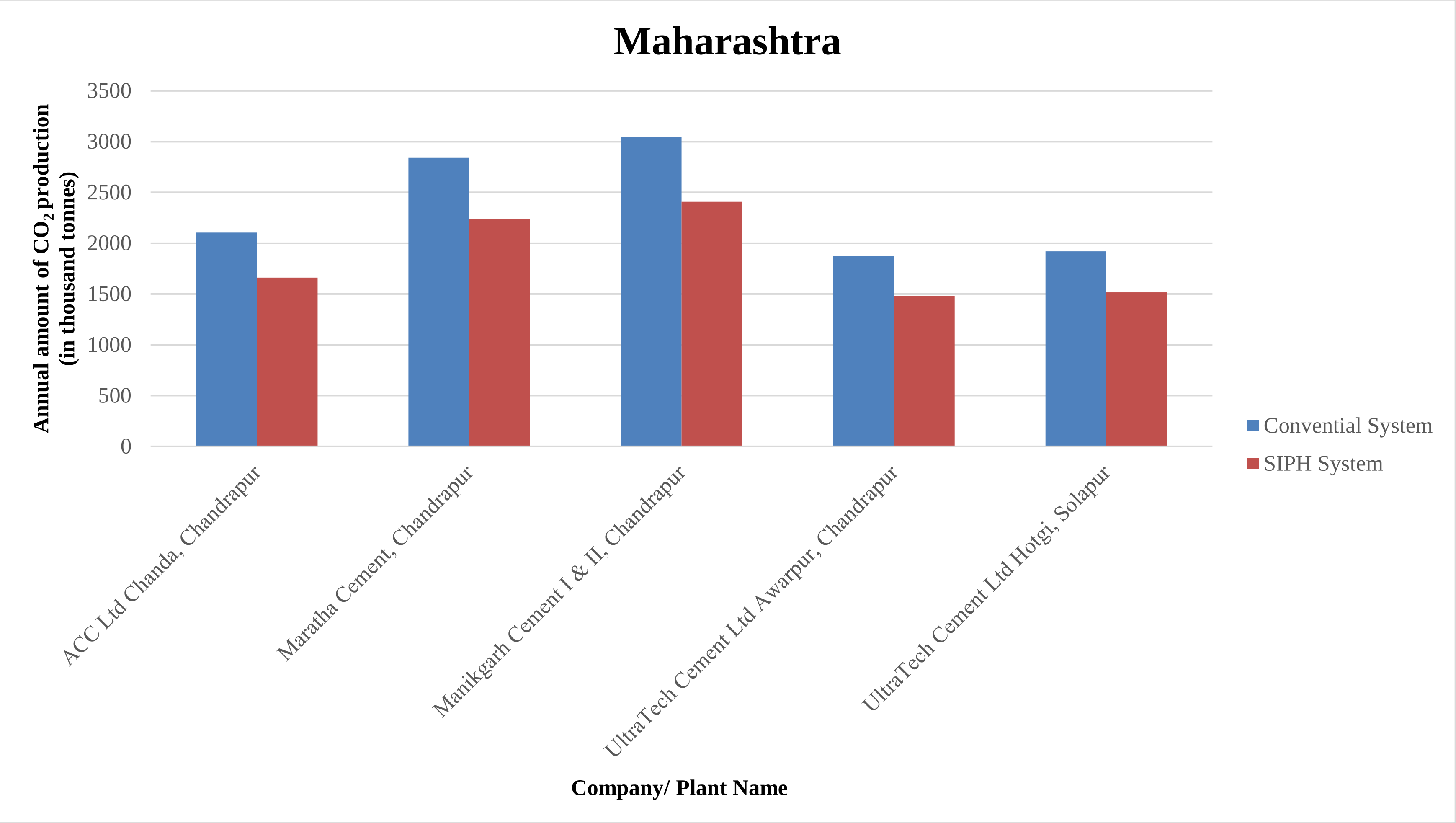
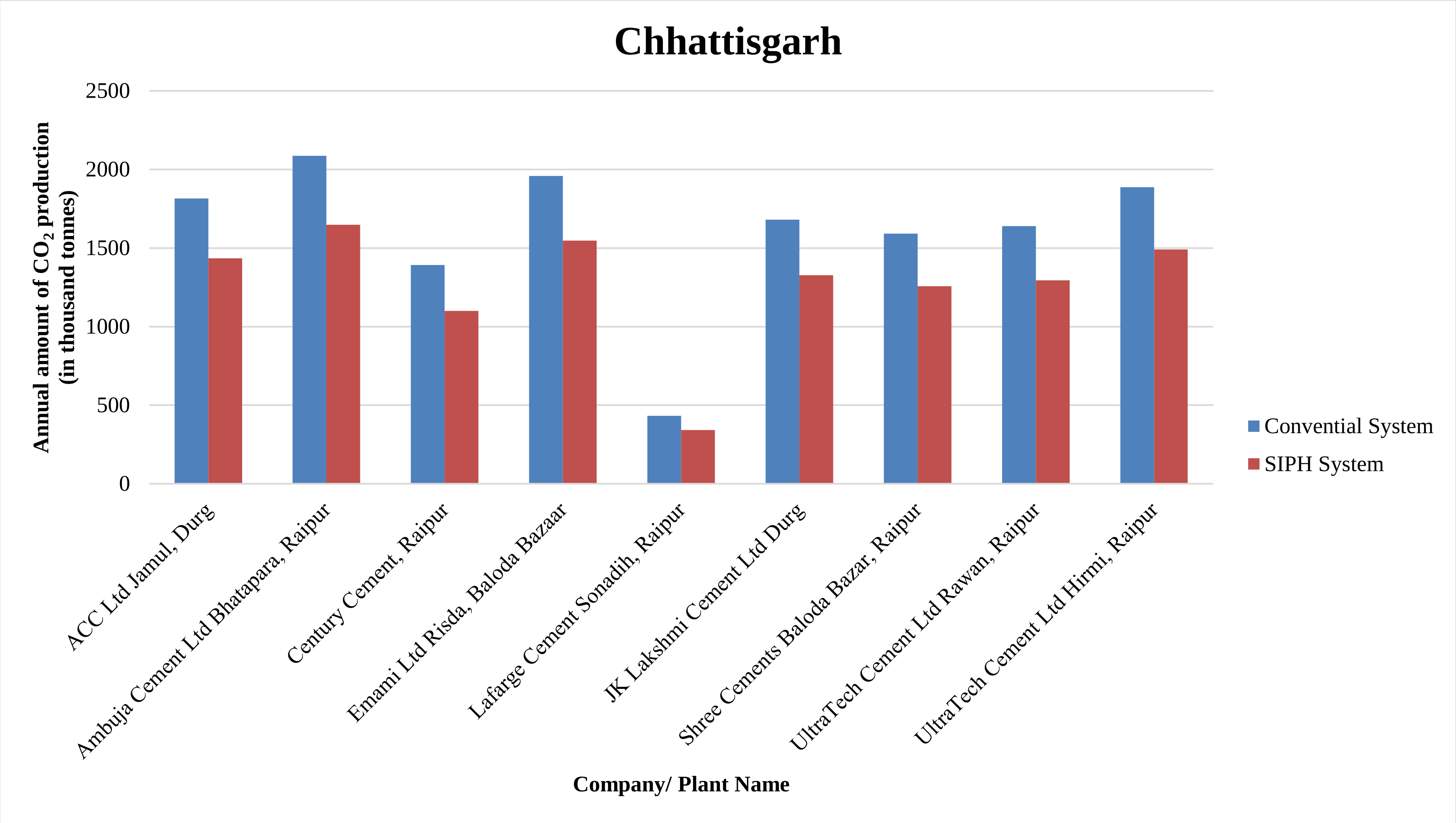


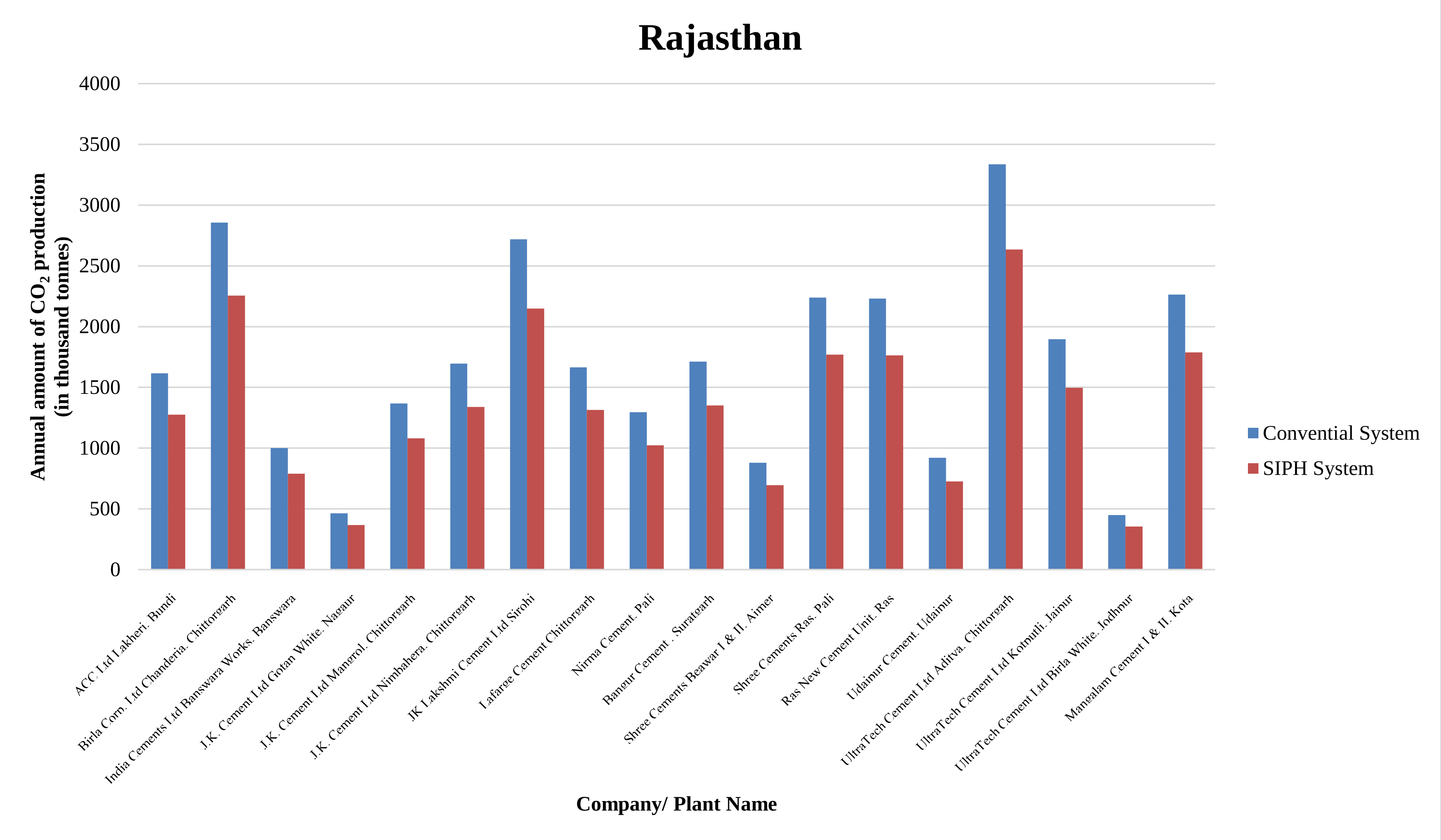
Fig.4.6 State-wise reduction of CO_2 emissions at Indian cement plants implementing SIPH system


Maharashtra
Annual amount of CO2 production (in thousand tonnes)
3500
3000
2500
2000
1500
1000
500
0
ACC Ltd Chanda, Chandrapur
Maratha Cement, Chandrapur
Manikgarh Cement I & II, Chandrapur
UltraTech Cement Ltd Awarpur, Chandrapur
UltraTech Cement Ltd Hotgi, Solapur
Company/ Plant Name
Convential System
SIPH System

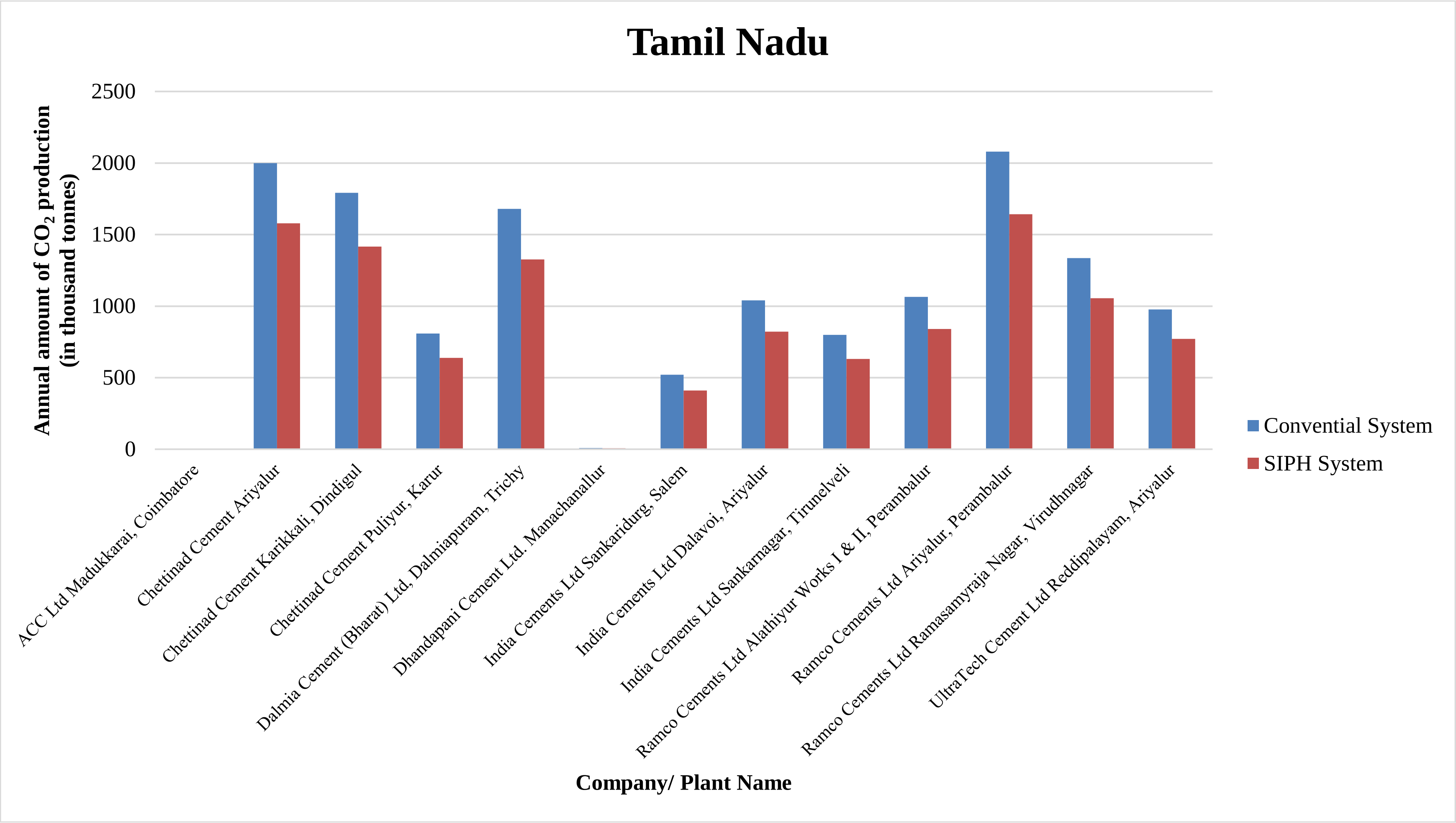
(a)


Chhattisgarh
Annual amount of CO_2 production (in thousand tonnes)
2500
2000
1500
1000
500
0
ACC Ltd Jamul, Durg
Ambuja Cement Ltd Bhatapara, Raipur
Century Cement, Raipur
Emami Ltd Risda, Baloda Bazaar
Lafarge Cement Sonadih, Raipur
JK Lakshmi Cement Ltd Durg
Shree Cements Baloda Bazar, Raipur
UltraTech Cement Ltd Rawan, Raipur
UltraTech Cement Ltd Hirmi, Raipur
Company/ Plant Name
Convential System
SIPH System

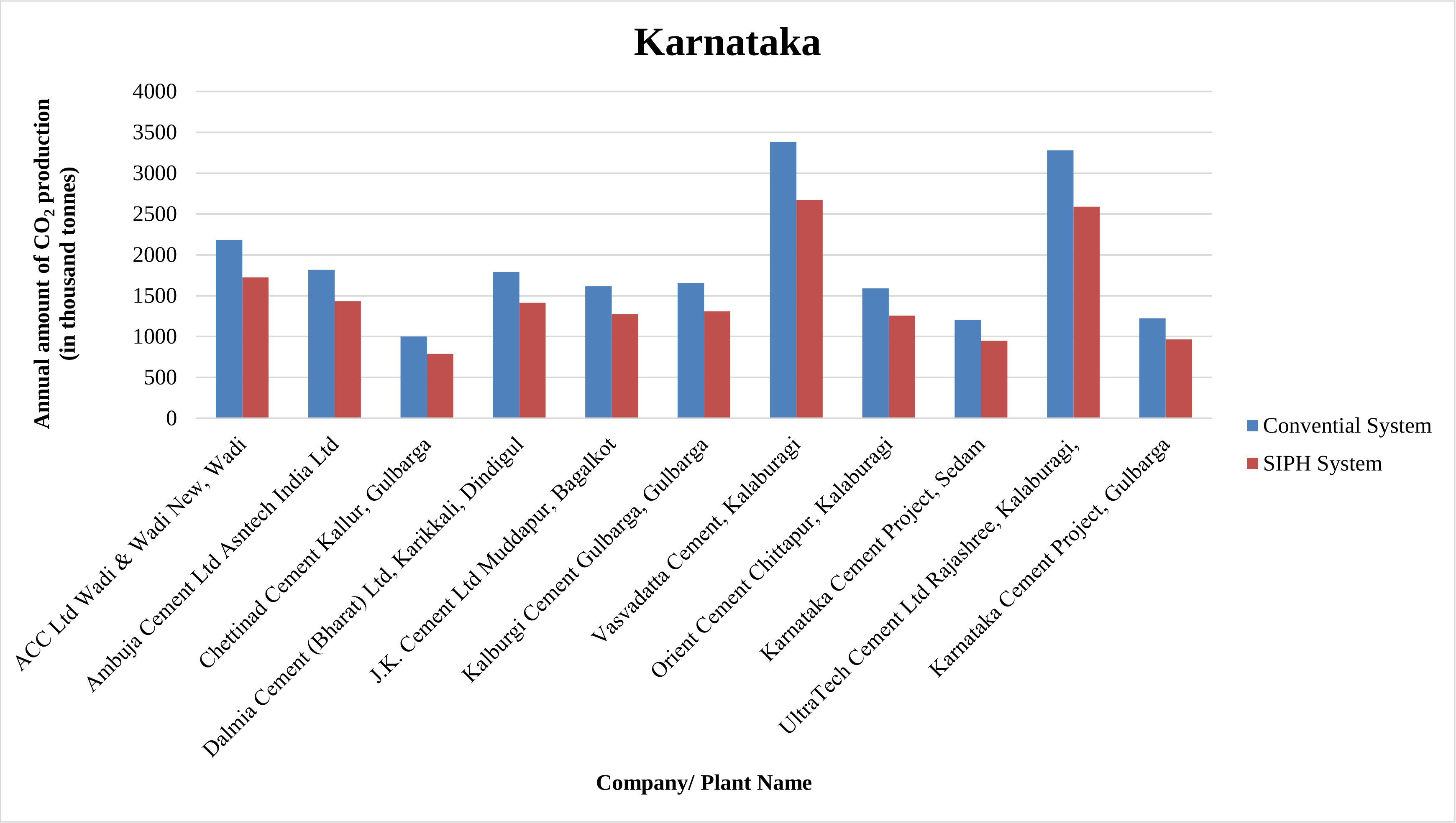
(b)


Rajasthan
4000
3500
3000
2500
2000
1500
1000
500
0
Annual amount of CO_2 production (in thousand tonnes)
ACC Ltd Lakheri. Bundi
Birla Corp. Ltd Chanderia. Chittorgarh
India Cements Ltd Banswara Works. Banswara
J.K. Cement Ltd Gotan White. Nagaur
J.K. Cement Ltd Mangrol. Chittorgarh
J.K. Cement Ltd Nimbahera. Chittorgarh
JK Lakshmi Cement Ltd Sirohi
Lafarge Cement Chittorgarh
Nirma Cement. Pali
Bangur Cement . Suratgarh
Shree Cements Beawar I & II. Ajmer
Shree Cements Ras. Pali
Ras New Cement Unit. Ras
Udaipur Cement. Udaipur
UltraTech Cement Ltd Aditya. Chittorgarh
UltraTech Cement Ltd Kotputli. Jaipur
UltraTech Cement Ltd Birla White. Jodhpur
Mangalam Cement I & II. Kota
Company/ Plant Name
Convential System
SIPH System

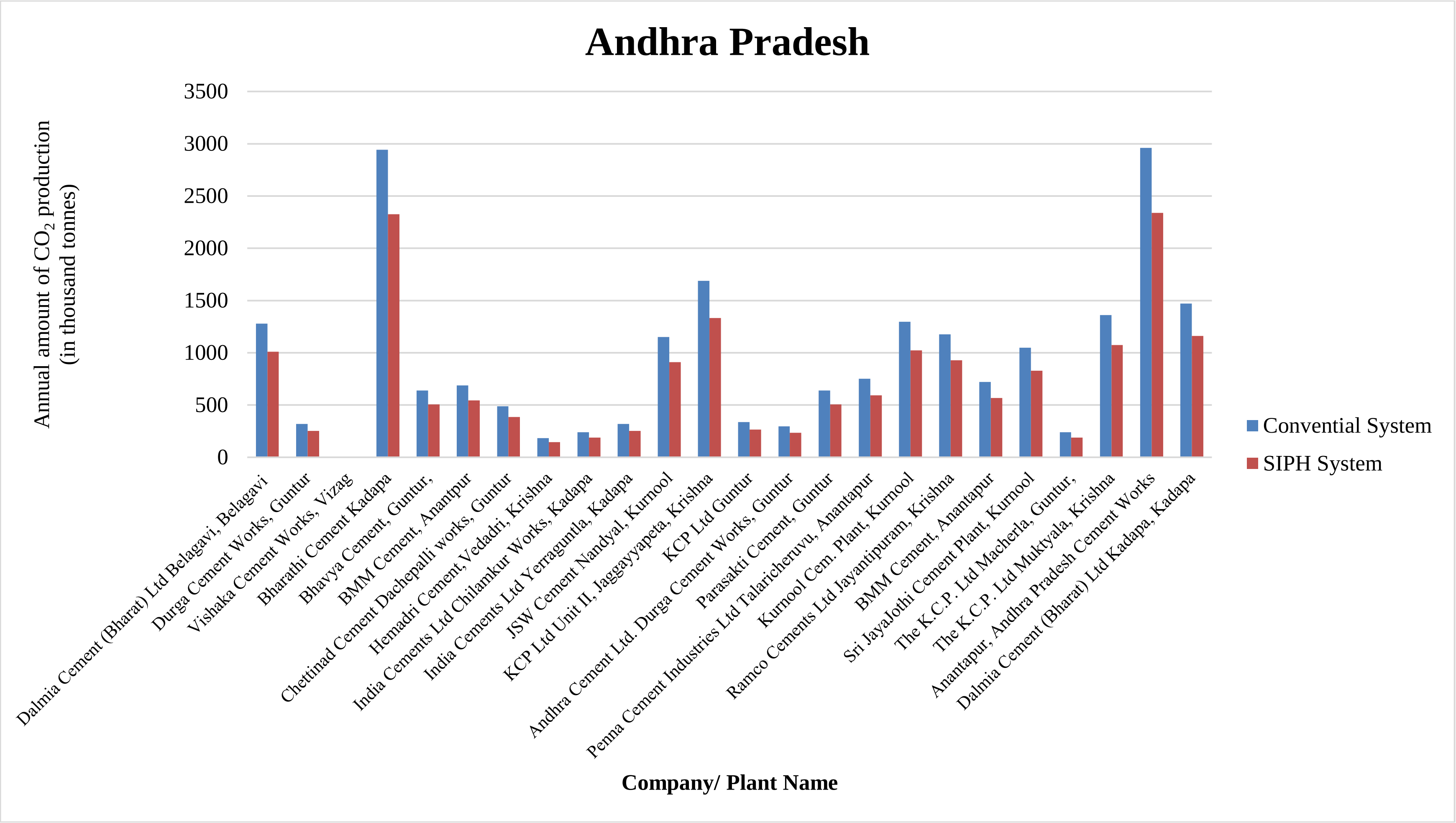
(c)


Tamil Nadu
Annual amount of CO_2 production (in thousand tonnes)
2500
2000
1500
1000
500
0
ACC Ltd Madukkarai, Coimbatore
Chettinad Cement Ariyalur
Chettinad Cement Karikkali, Dindigul
Chettinad Cement Puliyur, Karur
Dalmia Cement (Bharat) Ltd, Dalmiapuram, Trichy
Dhandapani Cement Ltd. Manachanallur
India Cements Ltd Sankaridurg, Salem
India Cements Ltd Dalavoi, Ariyalur
India Cements Ltd Sankarnagar, Tirunelveli
Ramco Cements Ltd Alathiyur Works I & II, Perambalur
Ramco Cements Ltd Ariyalur, Perambalur
Ramco Cements Ltd Ramasamyraja Nagar, Virudhnagar
UltraTech Cement Ltd Reddipalayam, Ariyalur
Company/ Plant Name
Convential System
SIPH System

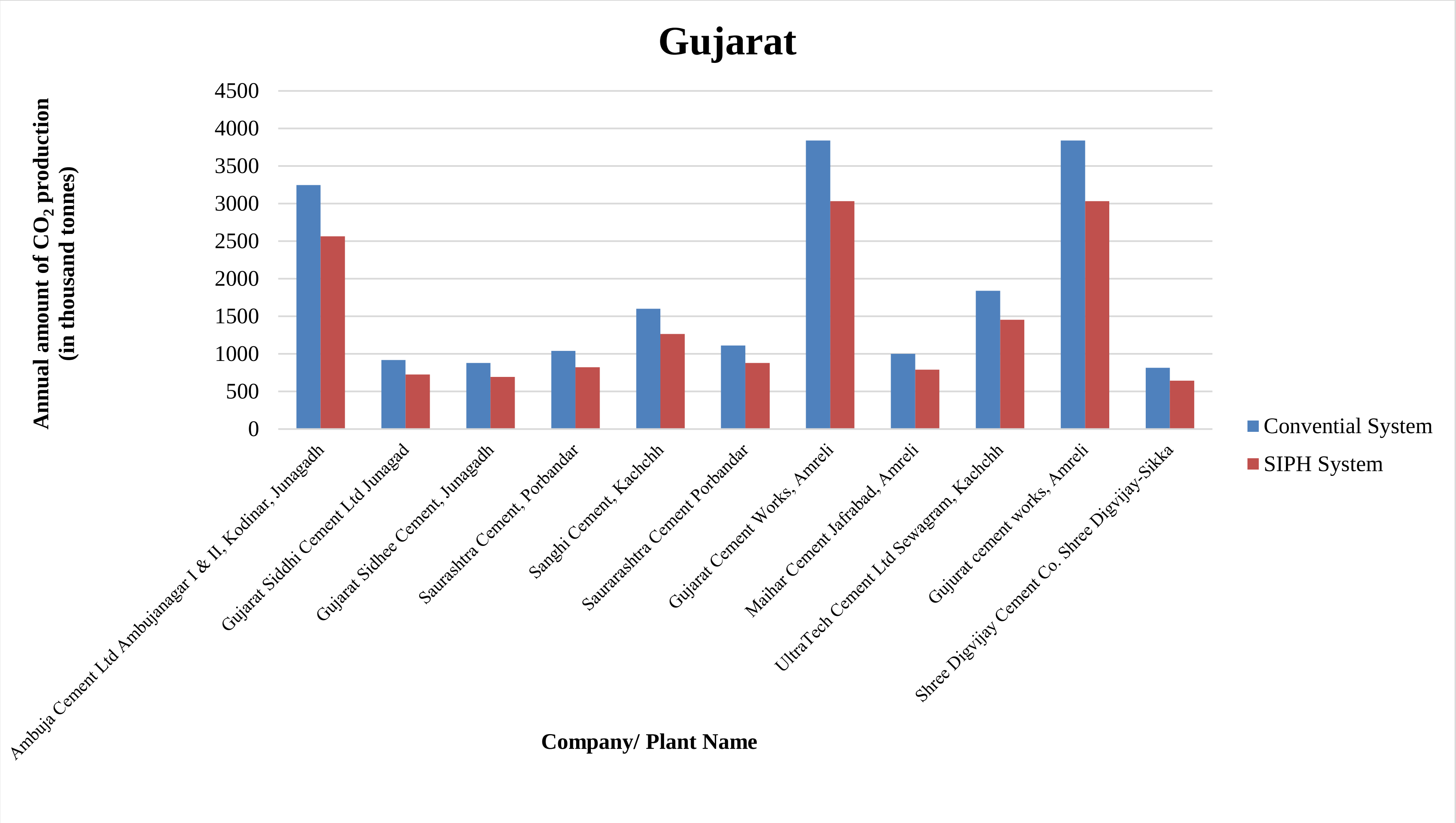
(d)


Karnataka
Annual amount of CO2 production (in thousand tonnes)
4000
3500
3000
2500
2000
1500
1000
500
0
ACC Ltd Wadi & Wadi New, Wadi
Ambuja Cement Ltd Asntech India Ltd
Chettinad Cement Kallur, Gulbarga
Dalmia Cement (Bharat) Ltd, Karikkali, Dindigul
J.K. Cement Ltd Muddapur, Bagalkot
Kalburgi Cement Gulbarga, Gulbarga
Vasvadatta Cement, Kalaburagi
Orient Cement Chittapur, Kalaburagi
Karnataka Cement Project, Sedam
UltraTech Cement Ltd Rajashree, Kalaburagi,
Karnataka Cement Project, Gulbarga
Company/ Plant Name
Convential System
SIPH System

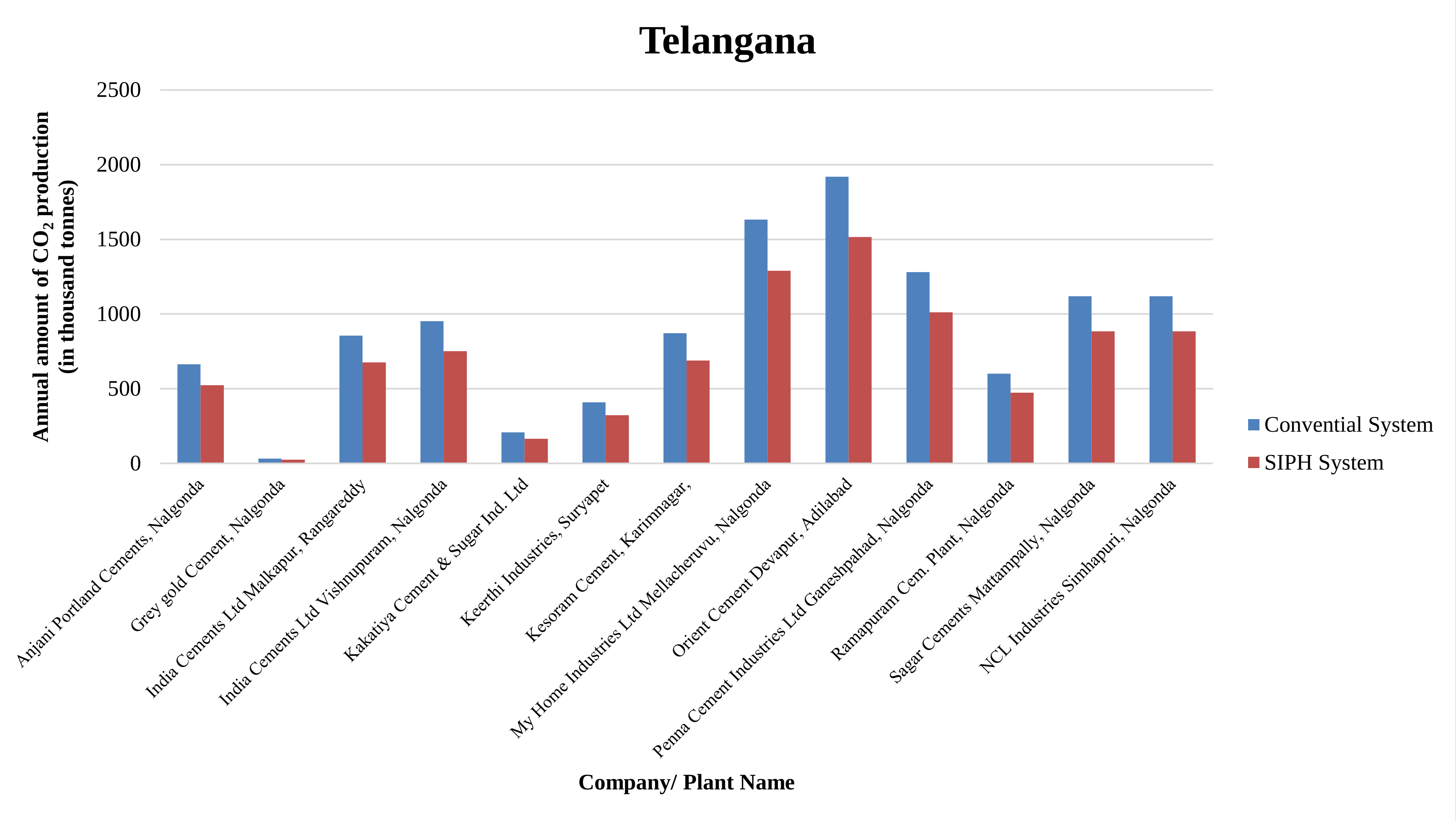
(e)


Andhra Pradesh
Annual amount of CO_2 production (in thousand tonnes)
3500
3000
2500
2000
1500
1000
500
0
Dalmia Cement (Bharat) Ltd Belagavi, Belagavi
Durga Cement Works, Guntur
Vishaka Cement Works, Vizag
Bharathi Cement Kadapa
Bhavya Cement, Guntur,
BMM Cement, Anantpur
Chettinad Cement Dachepalli works, Guntur
Hemadri Cement,Vedadri, Krishna
India Cements Ltd Chilamkur Works, Kadapa
India Cements Ltd Yerraguntla, Kadapa
JSW Cement Nandyal, Kurnool
KCP Ltd Unit II, Jaggayyapeta, Krishna
KCP Ltd Guntur
Andhra Cement Ltd. Durga Cement Works, Guntur
Parasakti Cement, Guntur
Penna Cement Industries Ltd Talaricheruvu, Anantapur
Kurnool Cem. Plant, Kurnool
Ramco Cements Ltd Jayantipuram, Krishna
BMM Cement, Anantapur
Sri JayaJothi Cement Plant, Kurnool
The K.C.P. Ltd Macherla, Guntur,
The K.C.P. Ltd Muktyala, Krishna
Anantapur, Andhra Pradesh Cement Works
Dalmia Cement (Bharat) Ltd Kadapa, Kadapa
Company/ Plant Name
Convential System
SIPH System

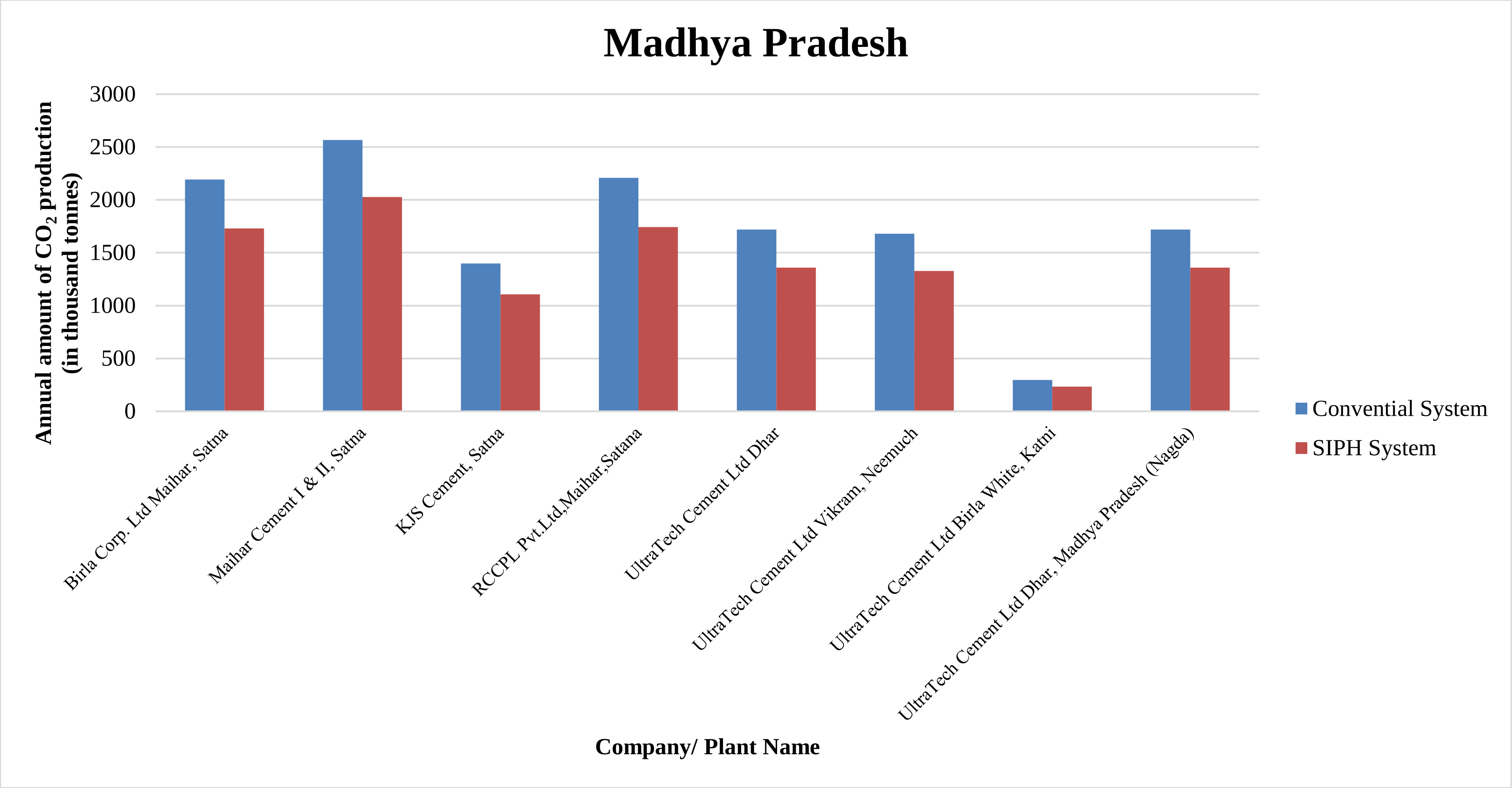
(f)


Gujarat
Annual amount of CO2 production (in thousand tonnes)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Ambuja Cement Ltd Ambujanagar I & II, Kodinar, Junagadh
Gujarat Siddhi Cement Ltd Junagad
Gujarat Sidhee Cement, Junagadh
Saurashtra Cement, Porbandar
Sanghi Cement, Kachchh
Saurarashtra Cement Porbandar
Gujarat Cement Works, Amreli
Maihar Cement Jafrabad, Amreli
UltraTech Cement Ltd Sewagram, Kachchh
Gujurat cement works, Amreli
Shree Digvijay Cement Co. Shree Digvijay-Sikka
Company/ Plant Name
Convential System
SIPH System

(g)


Telangana
Annual amount of CO2 production (in thousand tonnes)
2500
2000
1500
1000
500
0
Anjani Portland Cements, Nalgonda
Grey gold Cement, Nalgonda
India Cements Ltd Malkapur, Rangareddy
India Cements Ltd Vishnupuram, Nalgonda
Kakatiya Cement & Sugar Ind. Ltd
Keerthi Industries, Suryapet
Kesoram Cement, Karimnagar,
My Home Industries Ltd Mellacheruvu, Nalgonda
Orient Cement Devapur, Adilabad
Penna Cement Industries Ltd Ganeshpahad, Nalgonda
Ramapuram Cem. Plant, Nalgonda
Sagar Cements Mattampally, Nalgonda
NCL Industries Simhapuri, Nalgonda
Company/ Plant Name
Convential System
SIPH System

(h)



(i)

Fig.4.7 CO_2 mitigation potential of SIPH system across different states(a) Maharashtra (b) Chhattisgarh (c) Rajasthan (d) Tamil Nadu (e) Karnataka (f) Andhra Pradesh (g) Gujarat (h) Telangana (i) Madhya Pradesh in India

4.3 Design of solar thermal system for the investigated cement plant

This section discusses the findings of solar thermal application of the investigated plant. Power required for the calcination reaction and energy out from the solar reactor was calculated. Result includes the required mirror surface, number of heliostats, land surface, solar energy flux and net efficiency of the process. All these calculations are done by assuming the thermal losses as 15, 30 and 45 percent. Assumptions for the solar plant and the result are presented in Table 3.2 and 4.3 respectively.

Solar reactor output was 793 MW when 100% fossil fuel energy was replaced with solar energy and 45% thermal losses in solar reactor (Table 4.3). Furthermore, if 50% of the fossil fuel energy is replaced with solar energy then the solar output reduces to 398 MW. Mirror surface required for 100% energy replacement is 226 ha. Similarly, 15066 and 7600 are the number of heliostats required with each heliostat of surface area 150 m^2, for 100% and 50% energy replacement respectively. Total land surface required for 50% energy replacement considering minimum thermal loss was 370 ha. Net conversion efficiency depending on the thermal losses i.e., 15%, 30% and 45% was 44, 56 and 69.

Additionally, the CO_2 mitigated annually for the investigated plant was 419 thousand tons (Fig. 4.8).

Table 4.3 Solar power, mirror surface, number of heliostats and land surface requirements when concentrated solar energy is implemented in conventional cement production

Component	**Thermal losses (%)**	**Energy substituted (%)**					
		100	**90**	**80**	**70**	**60**	**50**
		Solar reactor					
Input power for calcination reaction (MW)		163	147	131	114	98	82
Thermal storage (MW)		273	246	218	191	164	137

		Solar field					
Solar power out from the solar reactor depending on power losses (MW)	15	513	462	410	359	308	258
	30	623	561	498	436	374	313
	45	793	715	635	555	476	398
Mirror surface depending on thermal losses (ha)	15	146	131	117	102	88	74
	30	178	160	142	124	106	89
	45	226	204	181	158	136	114
Number of Heliostat depending on thermal losses[#]	15	9733	8733	7800	6800	5866	4933
	30	11866	10666	9466	8266	7066	5933
	45	15066	13600	12066	10533	9066	7600
Land surface depending on thermal losses (ha)	15	730	655	585	510	440	370
	30	890	800	710	620	530	445
	45	1130	1020	905	790	680	570
Solar incident power on the heliostat field depending on power losses (MW)	15	641	577	512	448	385	322
	30	778	701	622	545	467	391
	45	991	893	793	693	595	497
Net conversion solar/chemical efficiency dep. on power losses (%)	15	68	68	68	68	68	68
	30	56	56	56	56	56	56
	45	44	44	44	44	44	44

[#] Considering a surface area of 150 m^2 for the heliostat

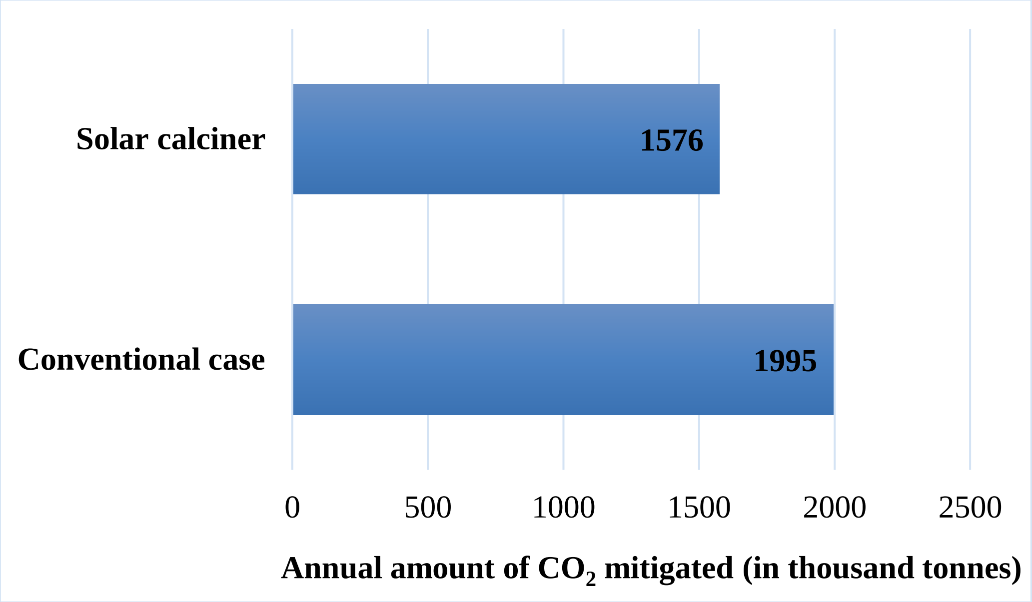


Fig.4.8 Potential of solar calciner technology to reduce CO_2 emissions at investigated cement plant

PBT and IRR were calculated for the plant under study and the result is shown in Fig. 4.9 and Fig. 4.10 respectively. PBT rises as the thermal losses in the solar reactor increase. Under the conditions of 45% thermal losses in the solar reactor and 100% energy replacement, the PBT was 10.4 years. IRR decreases as thermal losses in the reactor increase and maximum IRR is 10.20% when there is only 15% thermal loss in the solar reactor.

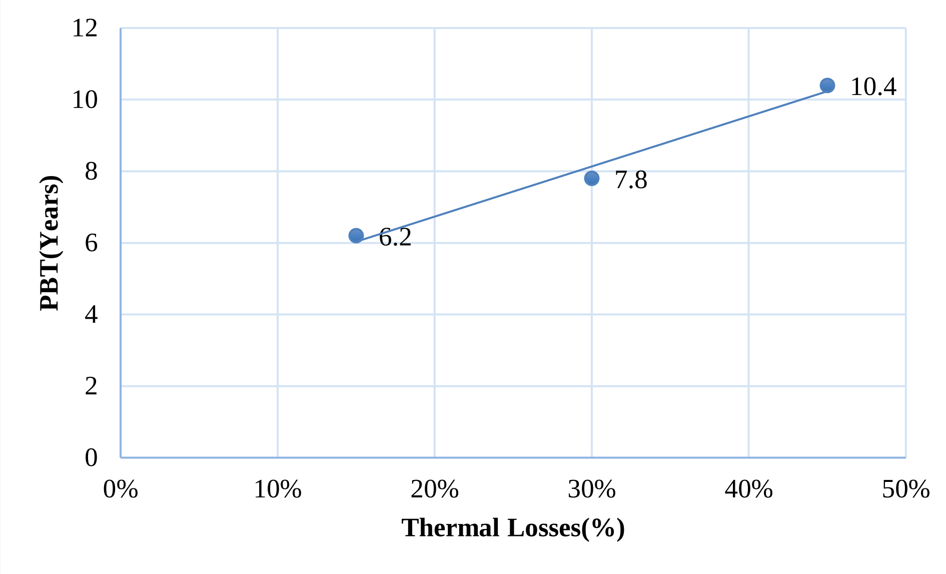


Fig.4.9 PBT analysis for a 6500 TPD solar cement plant based on the thermal losses from the solar reactor

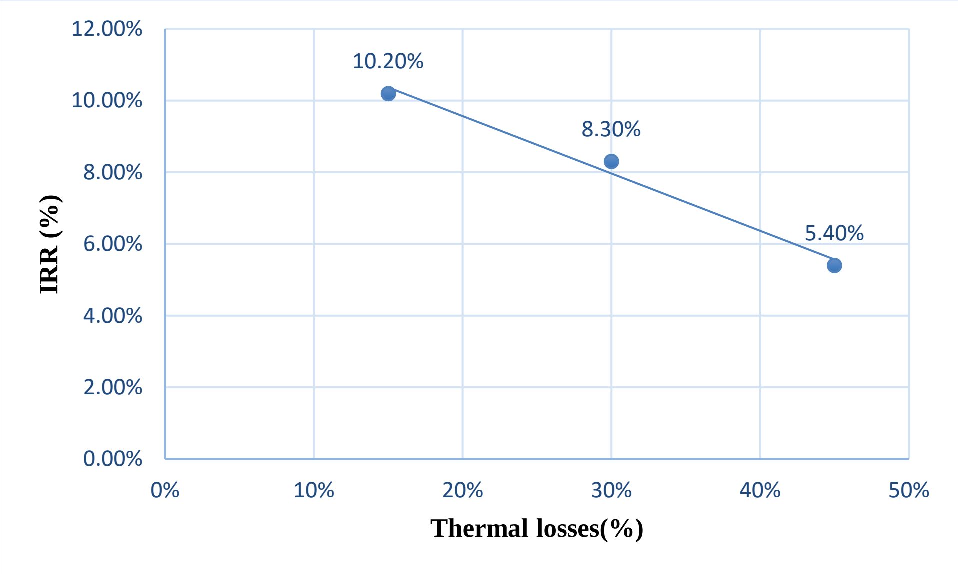


Fig.4.10 IRR analysis for a 6500 TPD solar cement plant based on the thermal losses from the solar reactor

4.4 Assessment of technical challenges

A discussion of the technical challenges associated with integrating CST technology with conventional cement production processes is presented in this section. Main challenges include transitioning new machinery from laboratory to industrial size and working under conditions like high temperatures. Risks are classified according to their level of risk, and the most critical risks are discussed. Each step of the new process is associated with technical risks, as described.

4.4.1 Preheater tower load capacity

Since there is a significantly greater amount of raw material to be calcined than in a traditional plant, the load-bearing capability of the preheater tower must be evaluated. This is because extra calcined material may be used during the night when solar energy is unavailable.

4.4.2 Transportation of raw and calcined material

This is based on the assumption that raw material is supplied to the solar reactor from the preheater tower's final stage. There is a major issue here because raw material reaches 800℃ while calcined material reaches 900℃. As a result of such high temperatures, a specific chemical reaction has already been initiated. These reactions produce sticky products that quickly form layers and coatings in the conveying pipes. Additionally, conveying system thermal losses also need to be considered. Therefore, pneumatic and mechanical systems should be used while transporting the hot raw material. Particle type pneumatic conveying systems are mostly used for CST projects due to less exergetic losses and the flux constraints while heating fluid through tubes (Guo et al., 2019). A wide range of companies can provide pneumatic conveying equipment for handling materials at high temperatures (Duarte et al., 2008; Wypych, 1999).

4.4.3 Scaling up solar reactors

Scaling up solar reactors involves increasing the size and capacity of solar reactor systems to enhance their efficiency and ability to meet energy demands. Design of the solar reactor is based on the model created and examined by Meier et al., (2006). Design of the solar reactor should concentrate on finding solutions to and recognizing new technical problems and limitations, such as insulating materials, system for high-rate material feeding, heat recovery systems, etc. Multi-reactor solar tower design is probably necessary to scale the solar reactor.

4.4.4 Storing of calcined material

A lot of development has been done in the field of thermal storage for CSP plants. Molten salts, phase changes, and solid materials are all aspects of development. Latent heat storage (LHS) is one of the recent topics in the field of thermal energy storage for concentrating solar thermal system. Energy is stored in LHS through the phase transition of the storing material (Nithyanandam et al., 2017). However, the challenge is applying this knowledge to store calcined material at 900 C. The U.S. government has sponsored new advancements and research programmes through NREL lab (González and Flamant, 2014) and SANDIA laboratories (Gregory, 2011) to construct storage tanks at 700°C, even if the current commercial applications function at roughly 500°C. Working with calcined material is easier because corrosion and solidification won't occur. Furthermore, these high temperatures already initiate chemical reactions in storage tanks and silos, resulting in sticky, layered chemicals.

Chapter five represents the conclusion of the entire observations made for both the proposed systems in this Thesis. Further, the entire observations are concluded with recommendations for future work that may enlighten the researchers to move ahead for further possible developments in this field for the betterment of the environment, and society.

CHAPTER: 5

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

This chapter represents the conclusions of the entire research work. Study shows that it is feasible to implement concentrated solar energy for the calcination process in cement production. Utilizing a central tower system with a solar reactor atop the tower is the best way to integrate CST technology into a conventional cement plant. Suggested design model does not need any major changes in the conventional plant. Solar reactor's thermal loss should not be more than 45%. Further, the entire observations are concluded with future scope that may enlighten the researchers to move ahead for the additional possible developments in this field for the betterment of society, environment, and the sustainable growth of human beings.

5.1 CONCLUDING REMARKS

The potential of implementing concentrated solar energy for the calcination process in cement production and consequent carbon mitigation has been analyzed. Economic analysis of the proposed design model was done through PBT and IRR. A case study was done on a conventional cement plant that is situated at a location with a DNI value of 438 (W/m^2). Based on the present study, following conclusions are framed:

i. The annual thermal energy savings by the use of solar calciner reactors was found to be 771.35 PJ.

ii. When all of the calciner's required thermal energy is replaced by solar energy, a maximum of 21% of the total CO_2 emission may be prevented.

iii. The usage of concentrated solar energy can prevent an estimated 45.193 MT of CO_2 emissions.

iv. Solar resource for the chosen plant location permits operation for an average of 12 hours per day. 9 hours of these 12 hours are usable, with the remaining 3 hours being utilized to heat up and cool down the solar reactor.

v. Utilizing a central tower system with a solar reactor atop the tower is the best way to integrate CST technology into a conventional cement plant. Suggested design model does not need any major changes in the conventional plant.

vi. Solar reactor's thermal loss should not be more than 45%.

vii. Economic analysis of the design model shows that PBT increases as thermal losses in solar reactor increase. IRR is also not attractive for 45% thermal losses in solar reactor.

viii. There are a lot of barriers that exist while implementing CST technology. Scaling up solar reactors, transportation system for raw and calcined materials, and storing of calcined materials are the major barriers.

ix. The conventional cement plant that is situated in a location with a DNI value of more than 438 (W/m^2) can use this solar design model. The conventional plant must have adequate land for installing a large number of heliostats.

It can be concluded from the results that concentrated solar energy can be successfully implemented for the calcination process in cement manufacturing. This study will be helpful for industries looking to replace thermal energy with green energy. Additionally, use of concentrated solar energy for different processes of cement production will reduce the carbon emissions to the environment. Economic analysis was performed and the PBT and IRR for the proposed design model were calculated. It also highlights the most recent findings, making it a valuable research resource.

5.2 SCOPE FOR FUTURE WORK

This research has presented the potential of implementing concentrated solar energy for the calcination process in cement production and consequent carbon mitigation. There is much work remaining to be completed, which can be used to improve this research. A variety of research work could be presented, as mentioned here.

The bottleneck issue of cement production is driven by solar power. A more detailed investigation of this subject, like the heat transfer in reactor, preheater, precalciner and other key equipment is encouraged.

It would also be interesting to choose the inner structure of the reactor rather than the position of reactor for efficient thermal supply.

Another aspect to consider in future work is to design of the reactor would be the key point to achieving an efficient thermal energy supply from solar energy.

5.3 SOCIAL IMPACT

Applications of solar thermal energy for the calcination process in the cement industry had a lot of impact on society which is as follows:

- Solarization in the cement sector can produce job requirements as it needs skilled labourers for installation, operation and maintenance.
- Solar thermal energy may improve health and quality of life by providing access to modern, clean energy services and by reducing the harmful greenhouse gas emissions to the atmosphere.
- Furthermore, it can reduce energy costs and enhance energy security by providing a stable and fairly priced source of electricity and heat, especially in remote or isolated areas with expensive or limited grid connections.

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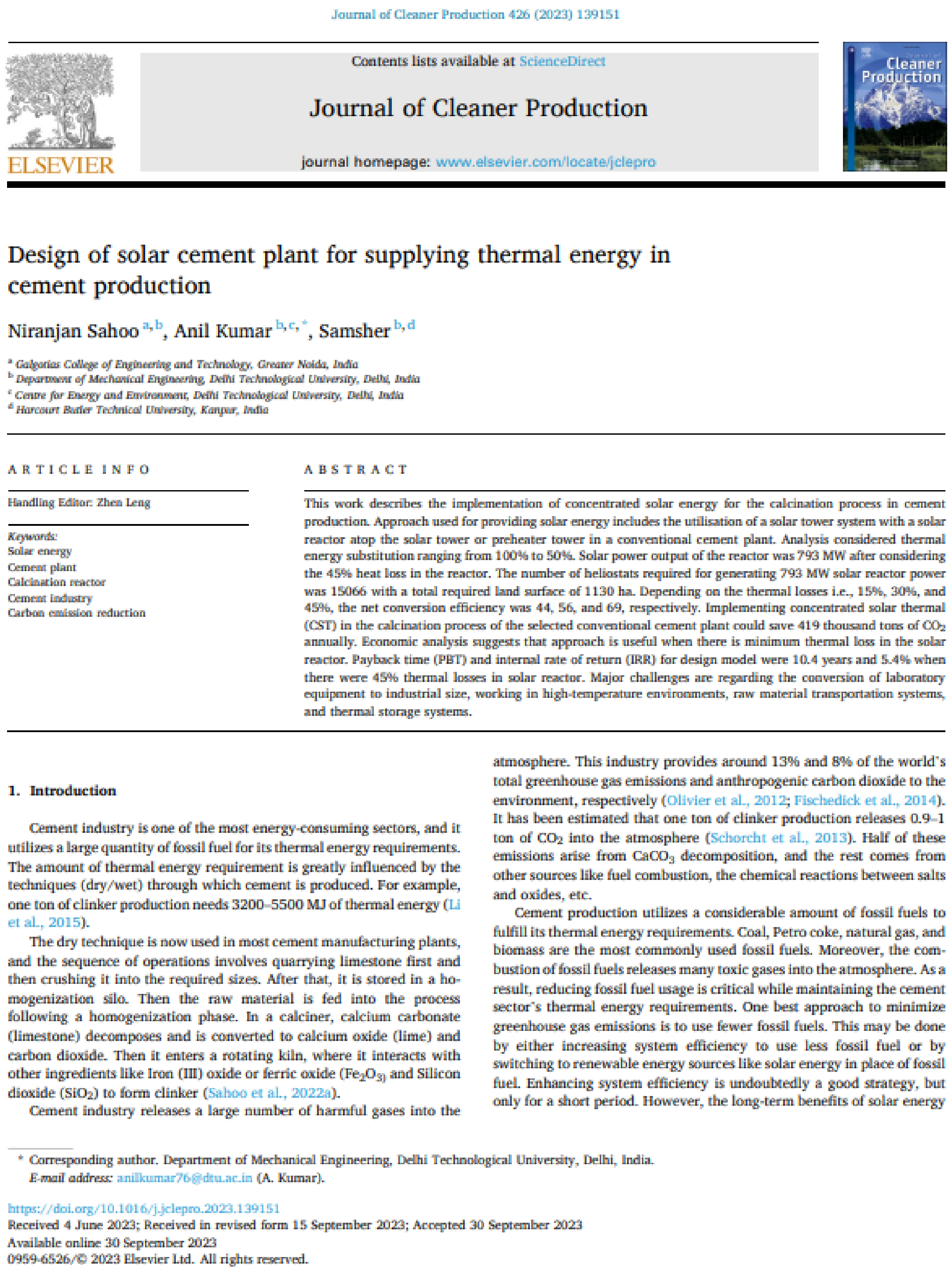
PUBLICATIONS



Journal of Cleaner Production 426 (2023) 139151

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Design of solar cement plant for supplying thermal energy in cement production

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ARTICLE INFO

Handling Editor: Zhen Leng

Keywords:
Solar energy
Cement plant
Calcination reactor
Cement industry
Carbon emission reduction

ABSTRACT

This work describes the implementation of concentrated solar energy for the calcination process in cement production. Approach used for providing solar energy includes the utilisation of a solar tower system with a solar reactor atop the solar tower or preheater tower in a conventional cement plant. Analysis considered thermal energy substitution ranging from 100% to 50%. Solar power output of the reactor was 793 MW after considering the 45% heat loss in the reactor. The number of heliostats required for generating 793 MW solar reactor power was 15066 with a total required land surface of 1130 ha. Depending on the thermal losses i.e., 15%, 30%, and 45%, the net conversion efficiency was 44, 56, and 69, respectively. Implementing concentrated solar thermal (CST) in the calcination process of the selected conventional cement plant could save 419 thousand tons of CO_2 annually. Economic analysis suggests that approach is useful when there is minimum thermal loss in the solar reactor. Payback time (PBT) and internal rate of return (IRR) for design model were 10.4 years and 5.4% when there were 45% thermal losses in solar reactor. Major challenges are regarding the conversion of laboratory equipment to industrial size, working in high-temperature environments, raw material transportation systems, and thermal storage systems.

1. Introduction

Cement industry is one of the most energy-consuming sectors, and it utilizes a large quantity of fossil fuel for its thermal energy requirements. The amount of thermal energy requirement is greatly influenced by the techniques (dry/wet) through which cement is produced. For example, one ton of clinker production needs 3200–5500 MJ of thermal energy (Li et al., 2015).

The dry technique is now used in most cement manufacturing plants, and the sequence of operations involves quarrying limestone first and then crushing it into the required sizes. After that, it is stored in a homogenization silo. Then the raw material is fed into the process following a homogenization phase. In a calciner, calcium carbonate (limestone) decomposes and is converted to calcium oxide (lime) and carbon dioxide. Then it enters a rotating kiln, where it interacts with other ingredients like Iron (III) oxide or ferric oxide (Fe_2O_3) and Silicon dioxide (SiO_2) to form clinker (Sahoo et al., 2022a).

Cement industry releases a large number of harmful gases into the atmosphere. This industry provides around 13% and 8% of the world's total greenhouse gas emissions and anthropogenic carbon dioxide to the environment, respectively (Olivier et al., 2012; Fischedick et al., 2014). It has been estimated that one ton of clinker production releases 0.9–1 ton of CO_2 into the atmosphere (Schorcht et al., 2013). Half of these emissions arise from $CaCO_3$ decomposition, and the rest comes from other sources like fuel combustion, the chemical reactions between salts and oxides, etc.

Cement production utilizes a considerable amount of fossil fuels to fulfill its thermal energy requirements. Coal, Petro coke, natural gas, and biomass are the most commonly used fossil fuels. Moreover, the combustion of fossil fuels releases many toxic gases into the atmosphere. As a result, reducing fossil fuel usage is critical while maintaining the cement sector's thermal energy requirements. One best approach to minimize greenhouse gas emissions is to use fewer fossil fuels. This may be done by either increasing system efficiency to use less fossil fuel or by switching to renewable energy sources like solar energy in place of fossil fuel. Enhancing system efficiency is undoubtedly a good strategy, but only for a short period. However, the long-term benefits of solar energy

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https://doi.org/10.1016/j.jclepro.2023.139151
Received 4 June 2023; Received in revised form 15 September 2023; Accepted 30 September 2023
Available online 30 September 2023

Process Safety and Environmental Protection 179 (2023) 667–676

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.journals.elsevier.com/process-safety-and-environmental-protection

Potential of solar thermal calciner technology for cement production in India and consequent carbon mitigation

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ARTICLE INFO

Keywords:
Solar energy
Cement industry
Carbon emission reduction
Solar calcination
Solar cement plant

ABSTRACT

This study describes the potential of solar thermal calciner technology and consequent carbon mitigation for Indian cement industries. Approach used to provide solar energy involves the installation of a solar tower system with a solar reactor atop the solar tower or preheater tower in a conventional cement plant. For potential estimation, locations of the clusters of cement plants with their actual annual cement production have been identified. Based on the annual actual cement production, the yearly process heating demand for the calcination process for each cement plant is estimated. Solar irradiation of each location of the cement plant is identified, and the plants with direct normal irradiation (DNI) > 1700 kWh/m^2 /annum are considered. Total thermal energy saved is estimated as 133.36 PJ/annum and CO_2 mitigation is estimated as 7413.73 thousand tonnes.

1. Introduction

The cement industry is one of the leading energy-consuming sectors, and most of its energy is consumed while heating various processes. Energy required for process heating is fulfilled by burning fossil fuels. Burning of fossil fuels emits several harmful gases into the atmosphere, primarily carbon dioxide (CO_2). Global cement industries contribute 8% of the total anthropogenic carbon dioxide emissions into the atmosphere (Olivier et al., 2012). India is the second largest cement producer, with a total output of 330 million tonnes in 2021(Source: statista@2022), and consumed around 7% of the world's total cement production. The per capita cement consumption in the country was 235 kg in 2020–21, which is still relatively low compared to the world's average of 520 kg. Countries with the highest levels of cement per capita consumption in 2020 were China (1620 kg per person), Viet Nam (911 kg per person), and the U.S. (314 kg per person). Cement consumption in India has continuously increased from 28 kg in 1980–81 to 235 kg in 2020–21. To satisfy the need huge quantity of fossil fuel is needed. Hence, it is necessary to choose some other sources of energy like solar energy for fulfilling the thermal energy demand. Implementing solar energy in the cement industry saves fuel as well as reduces CO_2 emissions.

In literature, few studies have found that integrated solar energy with the cement industry for fulfilling the thermal energy requirement for various processes during cement production (Imhof, 2000; Meier et al., 2005; González and Flamant, 2014; Moumin et al., 2020). Imhof (2000) incorporated the solar energy-driven calciner for a conventional 3000 t/d clinker plant. Reactor efficiency was 86%, and the solar irradiation was expected to be over 2000 kWh/m^{2}a. Results showed that the solar-driven calciner could save 28% (20,000 t/a) and 9% (51,000 t/a) of coal and carbon dioxide compared to the conventional calciner. Meier et al. (2005) assessed the economic feasibility of a 50-ton daily production capacity lime plant operated by solar energy. Investigation considered two approaches, i.e., beam-down (B.D.) and top-of-tower (T. T.) solar plant design. Solar reactor used for the calcination reaction was capable of producing 1, 5, and 25 MW of power. Minimum Direct Normal Irradiation (DNI) required at a particular location to start a solar lime plant was 2300 kWh/m^2, or the state with at least 500–600 W/m^2 of solar irradiation can start the solar plant. Furthermore, 95% of the greenhouse gas emissions released by fossil fuel-based production of

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https://doi.org/10.1016/j.psep.2023.09.041
Received 4 December 2022; Received in revised form 18 August 2023; Accepted 15 September 2023

Environmental Development 44 (2022) 100767

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

Review on energy conservation and emission reduction approaches for cement industry

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ARTICLE INFO

Keywords:
Cement
Industry
Energy
Conservation
Saving
Clinker

ABSTRACT

Cement production utilizes a considerable amount of energy which is also responsible for different greenhouse gas emissions. This review aims to help the cement industry to select the best method for improving energy efficiency and emission reduction. Various energy conservation and emission reduction approaches are considered for raw meal preparation, clinker manufacturing and cement grinding and include energy conservation approaches in support process of cement manufacturing. Raw meal preparation, clinker manufacturing, and cement grinding recorded the highest thermal energy savings of 4.30 GJ/t, 2.4 GJ/t, and 0.29 GJ/t, respectively. Gravity-type silos are the best blending system for the dry process, saving a maximum of 4.30 GJ/t of thermal energy. Furthermore, the use of advanced roller mills, Waste gas from rotary kiln and Up-gradation of mill for finish grinding can save a maximum of 11.9 kWh/t, 17.84 kWh/t, and 25.93 kWh/t electrical energy, respectively. Additionally, the highest recorded emission reduction value was 10.45 $kgCO_2/t$, 112.61 $kgCO_2/t$ and 26.66 $kgCO_2/t$ which are possible through advanced roller mills, implementing preheater/precalciner kiln system and up-gradation of mill system, respectively. This work will facilitate the researchers in knowing the current status of energy-saving practices and will encourage them to further research in this field.

1. Introduction

Energy is one of the basic primary requirements for the existence and growth of any industrial sector. Generally, industrial energy consumption directly affects a country's economic growth. This sector consumes 54% of the World's total delivered energy which is very high compared to other industries. According to International Energy Outlook (2016), the energy consumption of all industrial sectors around the World is increasing by an average of 1.2% per year. The World's industrial sector energy consumption expects to reach 309 quadrillions of British Thermal Units in 2040. The cement industry is one of the energy-intensive industries which utilizes a sizeable amount of energy. Avami and Sattari (2007) found that the cement industries in Malaysia consumed about 12% of the country's total energy, while this value is 15% in Iran. Hence, national and international efforts are carried out to reduce energy consumption and emission level in the cement industry (Engin and Ari, 2005; Gielen and Taylor, 2009; Sheinbaum and Ozawa, 1998; Borghetti Soares and Tiomno Tolmasquim, 2000; Worrell et al., 2000; Wang, 2008).

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https://doi.org/10.1016/j.envdev.2022.100767
Received 27 May 2022; Received in revised form 22 September 2022; Accepted 10 October 2022

Solar Compass 8 (2023) 100064

Contents lists available at ScienceDirect

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Potential assessment of solar industrial process heating and CO_2 emission reduction for Indian cement industry

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ARTICLE INFO

Keywords:
Solar energy
Industrial process heating
Cement
Carbon emission
Calcination

ABSTRACT

For the Indian cement sector, a simple approach is presented to evaluate the potential of solar industrial process heating (SIPH) and the resulting decrease in CO_2 emissions. The first step was to identify the locations of cement plants with their annual installed capacity and their annual actual cement production. After that, the yearly process heating requirement for the calcination process at each cement plant has been estimated using the actual annual cement production value. Finally, using the concept of a top-of-tower (TT) solar plant design, the total thermal energy that could be saved has been estimated as 771.35 Petajoule (PJ) /annum. Finally, the adoption of the SIPH system with storage is expected to mitigate CO_2 emissions by 45.2 MT (Megatons) annually. By utilizing renewable energy sources in the cement manufacturing process, energy consumption and CO_2 emissions will be reduced.

1. Introduction

India contributed more than 7 % of the world`s installed capacity for cement production, placing it as the second largest manufacturer in the world. In 2021, India`s domestic cement production was nearly 294.4 MT, while its installed capacity was 500 MTPA (Mega tons per annum). India got a growth of 12.1 % in cement production from September 2021 to September 2022. It is backed up by the robust real estate market and significant government investment in smart city projects and urban infrastructure. It is supported by the high level of activity going on in real estate and high Government spending on smart cities and urban infrastructure. It is expected that the cement demand will reach 419.92 MT by 2027 [1]. India currently has 210 large plants and 350 mini plants with cumulative installed capacities of 410 MT and 11.10 MT respectively. Most of the large cement plants are situated in three states (Andhra Pradesh, Rajasthan and Tamil Nadu). The state-wise installed capacity and actual production of cement for the year 2020–21 are shown in Fig. 1(Source: Indian Minerals Yearbook 2021) [2].

Energy is the most fundamental need of any industry to sustain and grow. A considerable amount of thermal energy is utilized during the process heating while most of the processes operate in the temperature range between 400 °C and 1400 °C. Production of cement needs a tremendous amount of energy and it is in the form of thermal and electrical respectively. Thermal energy is utilized for heating various processes such as blending and homogenization, precalcination, pyro processing, etc., whereas electricity is used to operate air compressors, coolers, grinding units, lighting systems, etc. The thermal and electrical energy required for the different processes of cement production is shown in Fig. 2.

Cement use is rising quickly on an international scale. A huge quantity of thermal energy is needed to produce cement, which is in high demand. Most of the cement industries use fossil fuels for generating thermal energy. The most commonly used fossil fuels are coke, coal, biomass, natural gas, etc. Consumption of these fossil fuels generates a lot of greenhouse gases into the atmosphere which degrades the atmosphere day by day [4]. Hence, the use of fossil fuels should be limited and there must be some alternatives so that the cement sectors should not be disturbed. One of the best ways to come out of the problem is the use of renewable sources of energy. Solar energy can be effectively used to provide thermal energy for the different processes of cement manufacturing. Calcination is an important process of cement manufacturing and previous research suggested that concentrated solar energy could replace conventional fossil fuel. Solar reactors are used for calcining the raw materials which can be fixed at two different positions as shown in Fig. 3 [5–7].

Many researchers have investigated the potential of solar energy in cement manufacturing, as evidenced in a literature review [9–13].

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https://doi.org/10.1016/j.solcom.2023.100064
Received 12 July 2023; Received in revised form 30 September 2023; Accepted 8 November 2023

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This is to certify that the paper entitled **Solar Industrial Process Heating Prospects In Indian Cement Industries** authored by **NIRANJAN SAHOO, ANIL KUMAR and SAMSHER** has been presented at the **Second International Conference on Mechanical and Energy Technologies (ICMET-2021)** held during 28-29th Oct 2021.

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has participated in the 2nd International Conference on
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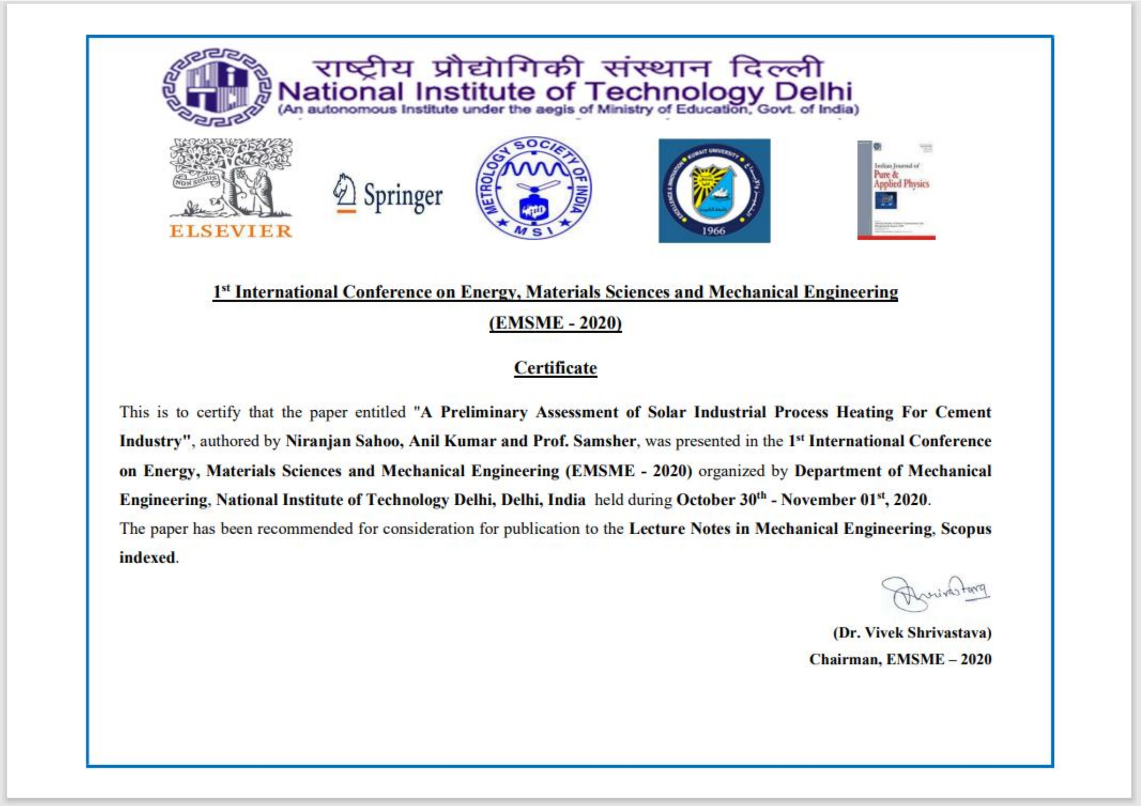

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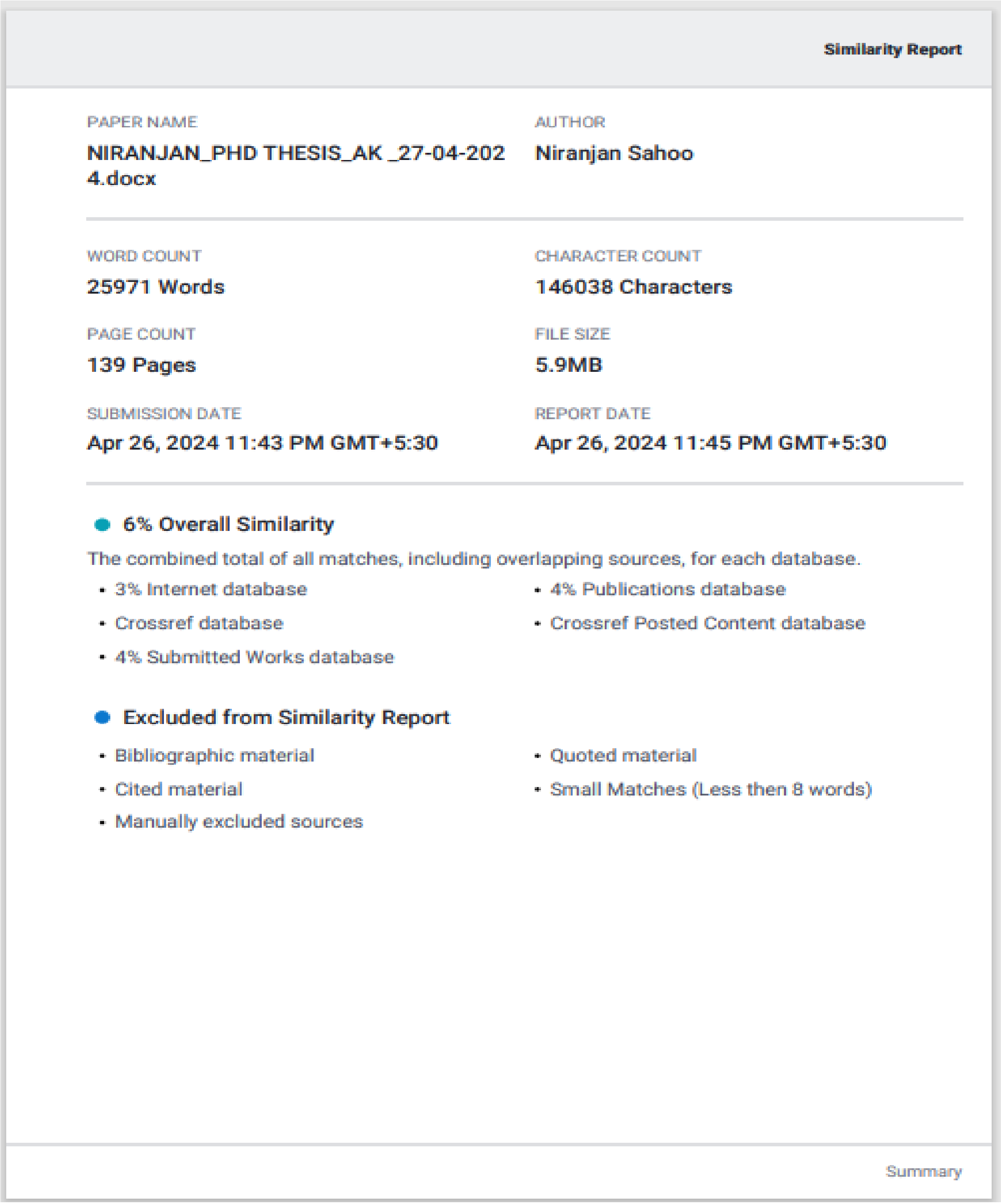

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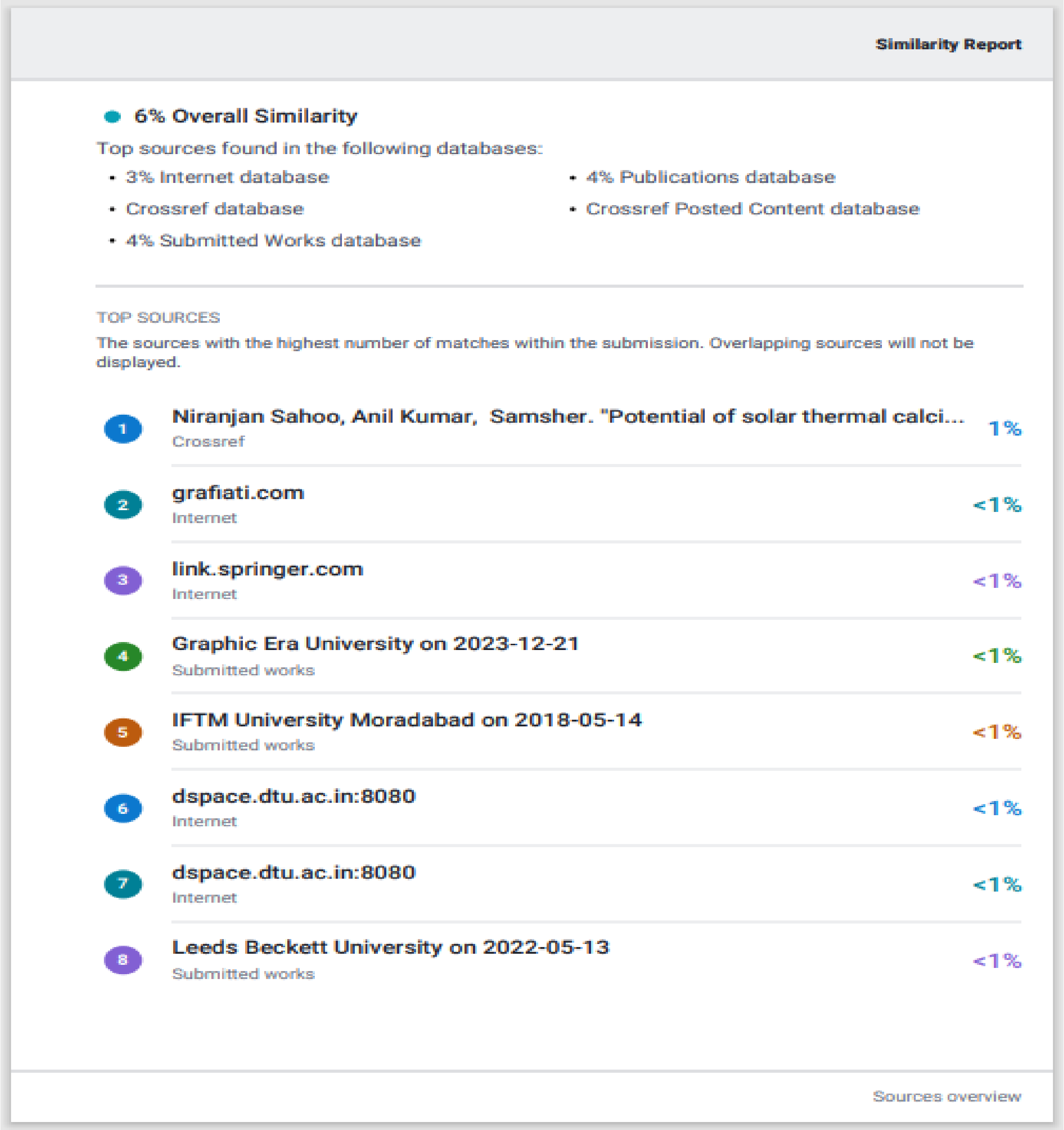

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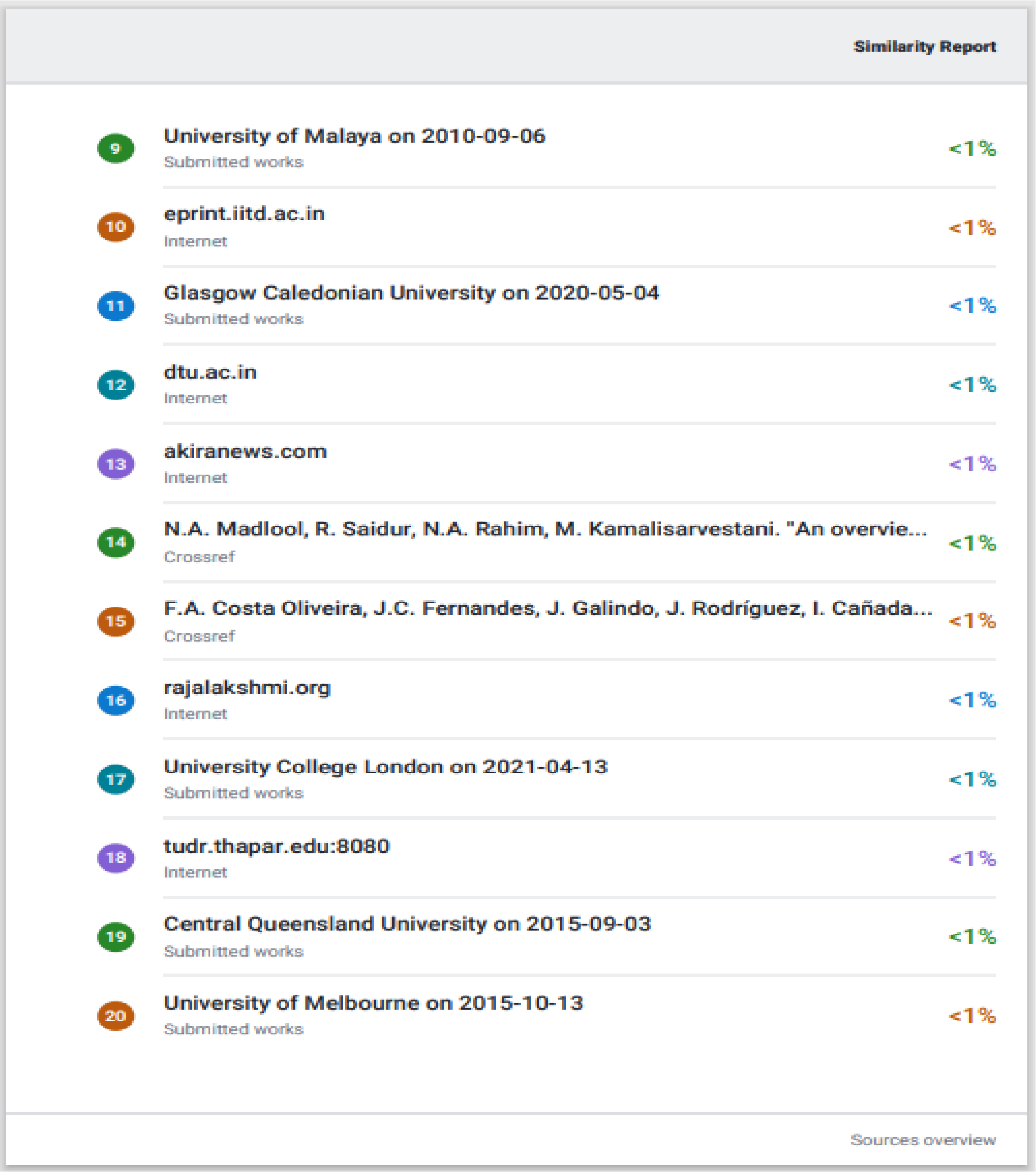

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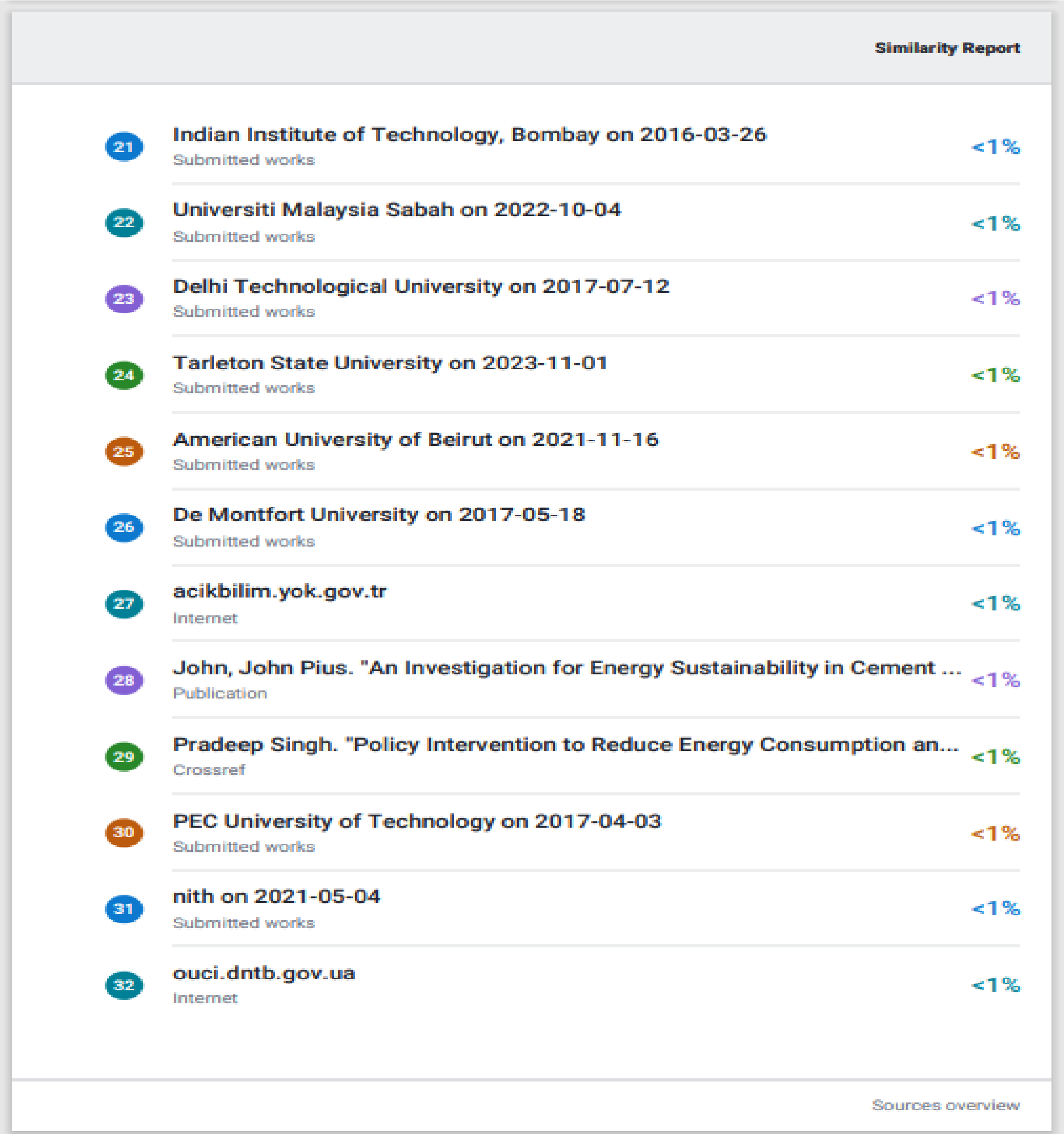

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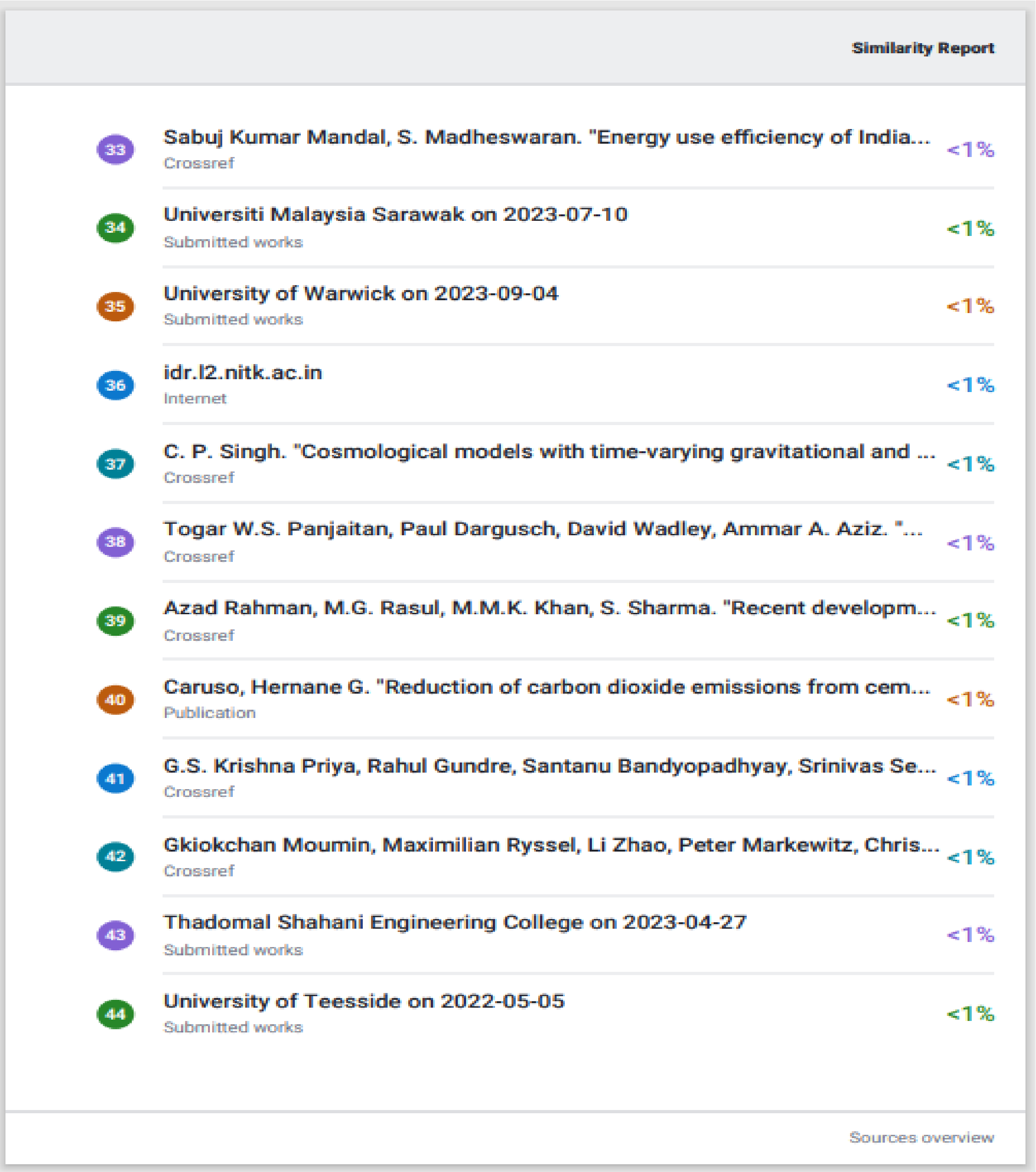

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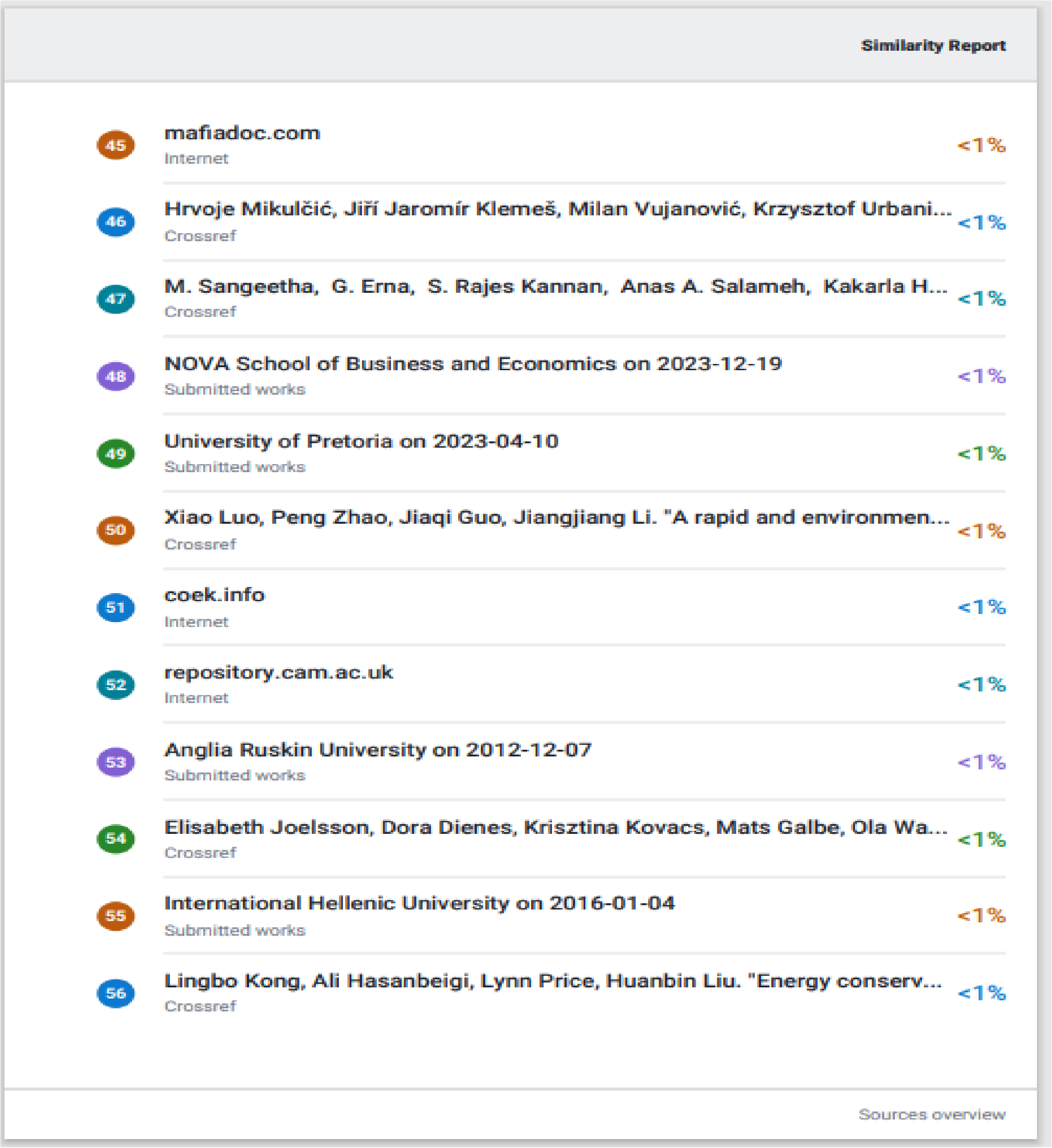

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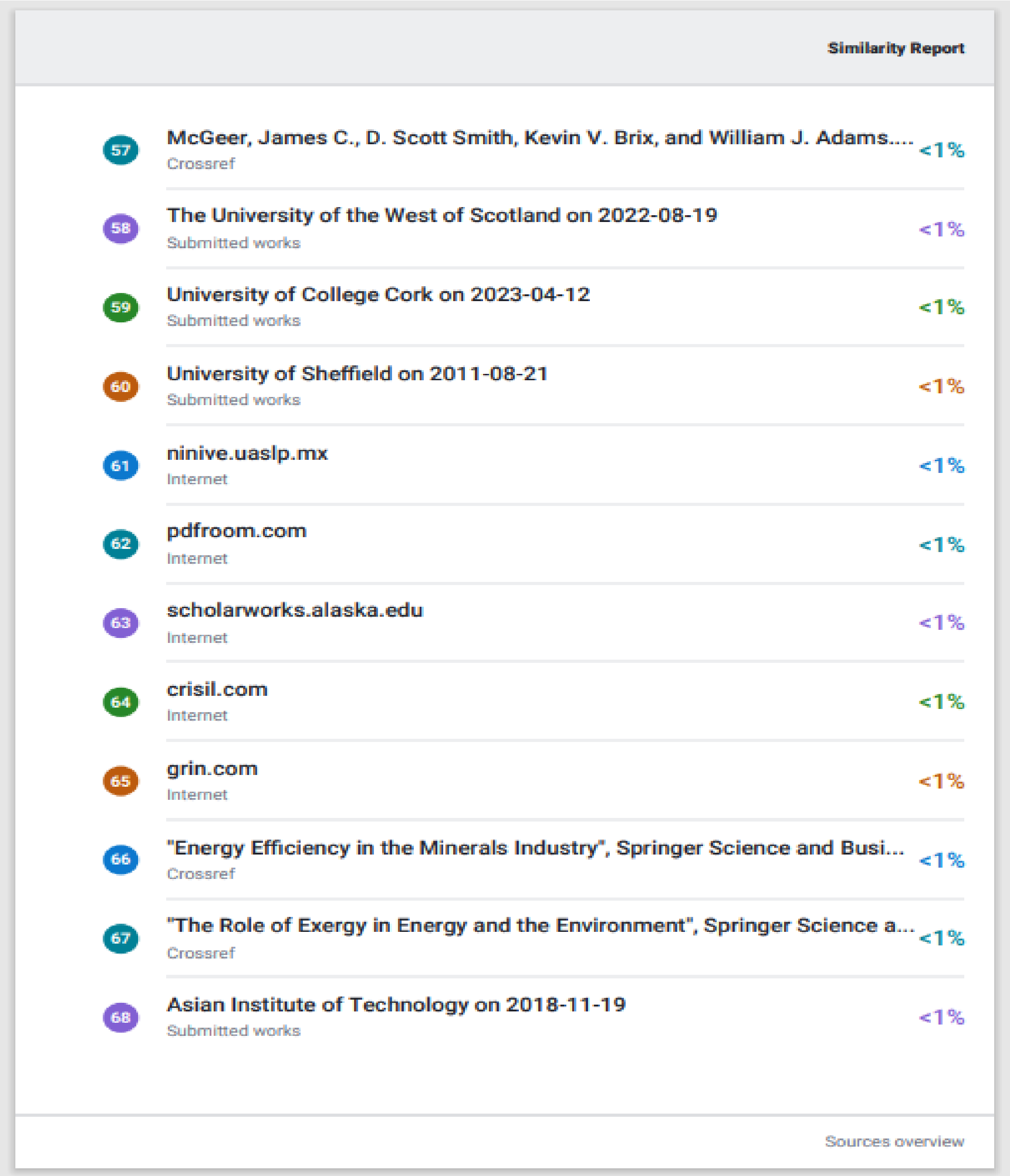

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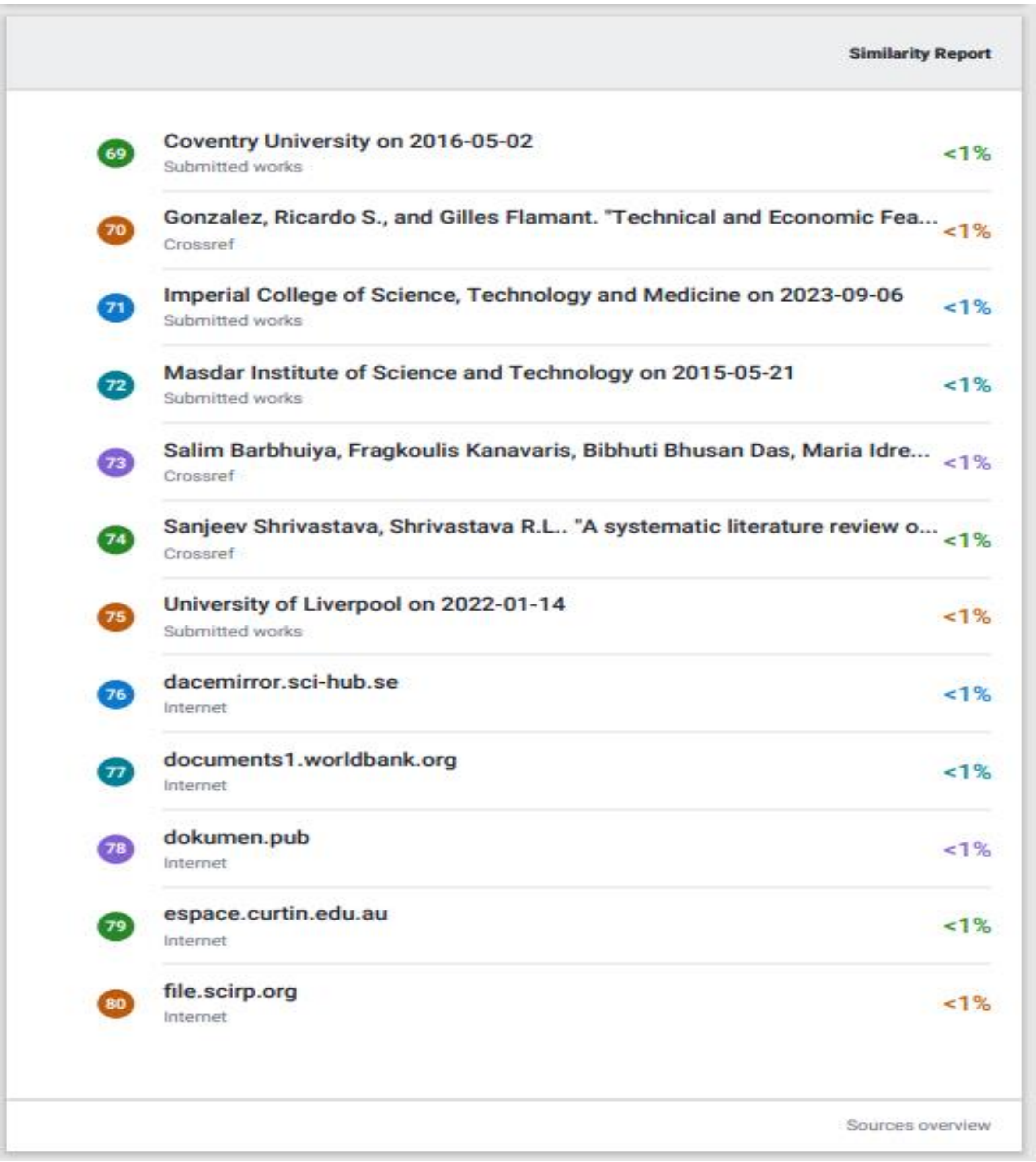

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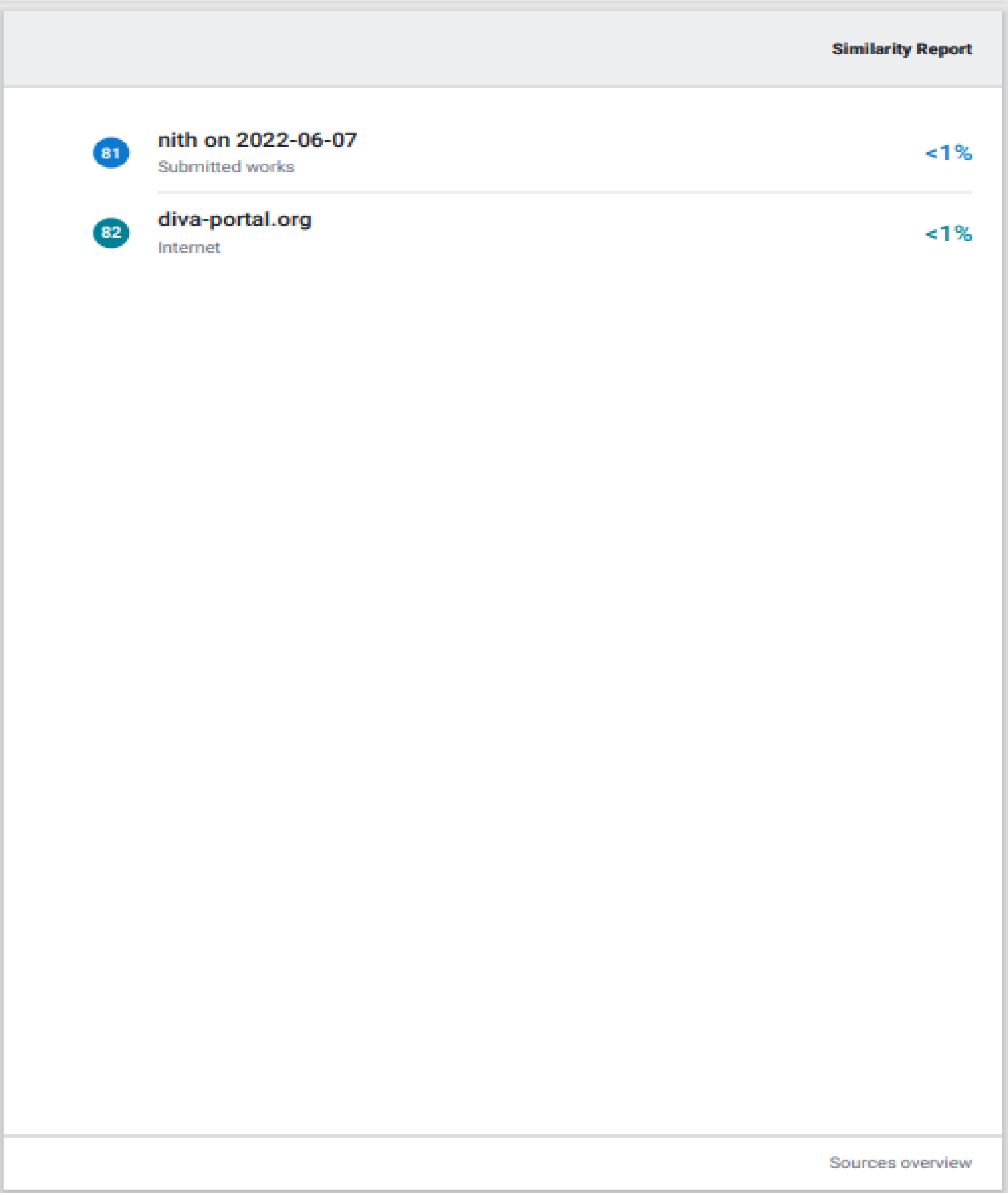

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Career Objective

Highly motivated and dedicated individual with technical and personal attributes with excellent teaching skills and knowledge of scientific research

Brief Introduction

I would like to Introduce myself as **Niranjan Sahoo** a research scholar and pursuing his Ph.D. at Mechanical Engineering Department with specialization in Thermal Engineering from Delhi Technological University, Delhi. Delighted to have authored numerous research articles published in **high-impact SCI** Journals, my noteworthy contributions include **four** significant publications as the First Author. One of them is in the esteemed "**Journal of Cleaner Production" (Impact Factor: 11.1, Q1)**". Additionally, I have published in the renowned "**Journal of Process Safety and Environmental Protection" (Impact Factor: 7.8, Q1)**. Over the past two years, I have published three SCI-indexed journals, moreover one paper is currently under review in **Journal of Solar Energy Engineering (ASME)**. My dedication to research was recognized with the **Commendable Research Excellence Award** at **Delhi Technological University** in April 2023 and also nominated for year 2024.

I have been engaged as a member of **Internal Quality Assurance Cell (IQAC) at GALGOTIAS EDUCATIONAL INSTITUTIONS**, which develop a mechanism for systematic reviews of study programs, and to ensure quality teaching-learning, research, knowledge generation and support services standards at an acceptable level. In addition, I am a member of the **MOOCs Committee**, which manages all matters pertaining to Swayam, Online Courses, MOOCs, and PARAKH, and the **Proctorial Board**, whose duties include maintaining order, enforcing campus policies, and guaranteeing a safe environment for everyone.

My dedication and hard work are evident in my sincere approach to my responsibilities. I have made significant contributions to the department through my exemplary teaching, research endeavors, and diligent fulfillment of various departmental duties (**including NBA, NAAC accreditation work**).

Academics

Qualification	**Board/university**	**Year**	**Percentage (%)**
Ph.D.	Delhi Technological University Delhi, India	Pursuing	7.50

M.Tech.	Jadavpur University, Kolkata	2009	8.16
B. E.	University College of Engineering, Burla	2005	64.98

Ph.D. Thesis Title

Energy Conservation and Emission Reduction Potential Through Solar Energy Applications in Cement Industry

Work Experienced

- Working as an Assistant Professor-II in Galgotias College of Engineering and Technology (Gr. Noida) from April 2014 to till now.
- Working as an Assistant Professor-1 in Accurate Institute of Management and Technology (Gr. Noida) from Aug 2012 to April 2014.
- Working as an Assistant Professor-I in Galgotias College of Engineering and Technology (Gr. Noida) from Aug 2011 to Aug 2012.
- Working as an Assistant Professor-1 in Accurate Institute of Management and Technology (Gr. Noida) from Aug 2010 to Aug 2011.
- Working as an Assistant Professor-1 in Noida Institute of Engineering and Technology (Gr. Noida) from Jul 2009 to Aug 2010.

Role and Responsibility

- Deliver lecture to the students and attain tutorial classes as well as Practical Classes.
- Offer required help to the students outer the classrooms if needed.
- Planned and implemented special college events with the proper coordination with the supportive officials along with the community representatives.
- Acting as a member of Proctorial Committee.
- Act as mentor for student.

Achievements

- I was honored to receive the **Research Excellence Award** for commendable research achievements in 2022 from DTU Delhi.
- Organizing member of “Recent Advances In Mechanical Engineering”, (RAME-2020) held on September 18-19, 2020. at DELHI TECHNOLOGICAL UNIVERSITY.
- GATE 2007 qualified with All India rank 259.
- GATE 2006 qualified with All India rank 347.
- Successfully completed the 4-week course "Teaching and Learning in Engineering (TALE)" organized by NPTEL during Feb-Mar 2019.

Publications

International Journal (04)

International Conference (03)

References:

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PERSONAL PROFILE

Strengths and Qualities	Self-Confident, Smart Working, Punctual
Hobbies and interest	Playing Table Tennis, Appreciating music & Cooking
Gender	Male
Nationality	Indian
Date of Birth	Jul 3, 1982
Languages Known	English, Hindi, Odia, Bengali
Permanent Address	LP-404, Prasanti Vihar, PO-KIIT, Bhubaneswar, Odisha-751024

I hereby declare that the information given above is correct to the best of my knowledge.

Date: 09-092024
Place: Delhi

Niranjan Sahoo