



**TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS**

THESIS NO.: M-416-MSREE-2024-2026

**Integrated Energy, Emissions, Financial, and CFD-Based Assessment of a
Tunnel Brick Kiln in Nepal**

by

Basil Sharma

A THESIS

**SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND
AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN
RENEWABLE ENERGY ENGINEERING**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
LALITPUR, NEPAL**

APRIL, 2026

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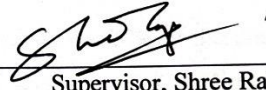
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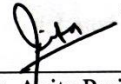
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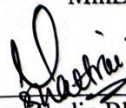
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ABSTRACT

The brick industry is one of the most energy-intensive and carbon-emitting industrial sectors in Nepal, while tunnel kilns account for less than 0.3% of the total kiln population. This study presents an integrated assessment of the energy performance, emission characteristics, financial feasibility, and transient CFD-based combustion behavior of a tunnel brick kiln operating in Nepal. Field measurements and production data were used to evaluate thermal efficiency, specific energy consumption (SEC), emissions, and project viability, while transient CFD simulation was applied to examine combustion behavior under stoichiometric, fuel-rich, and excess-air conditions for both coal and natural gas.

The measured thermal efficiency of the kiln was 46.15% by the direct method and 51.18% by the indirect method. The total SEC was 1.72 MJ/kg of fired brick, including a thermal SEC of 1.66 MJ/kg. Annual CO₂ emissions were estimated at 8,530.1 tons by the stack method and 8,811.97 tons by the fuel-based inventory method, with an emission intensity of 203–212 g CO₂/kg fired brick. Total greenhouse gas emissions were estimated at 8,539.636 tons CO₂ equivalent per year. Financial analysis showed that the kiln becomes economically viable above about 21–22% capacity utilization. The CFD results showed that stoichiometric combustion produced the most effective temperature field, while fuel switching from coal to natural gas could reduce annual energy use by 10,650.47 GJ/year (20%), CO₂ emissions by 4,461.78 tons/year (65.57%), and annual fuel cost by NPR 7,742,672.74 (12.27%).

Keywords: Tunnel brick kiln; CFD; specific energy consumption; thermal efficiency; CO₂ emission intensity; natural gas substitution; financial analysis; Nepal

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor Associate Professor Dr. Shree Raj Shakya and Assistant Professor Dr. Anita Prajapati for their invaluable guidance, encouragement, and constructive feedback throughout the course of this research. Their expertise and patience were instrumental in shaping this thesis.

I am also thankful to the members of my thesis committee, for their insightful comments and suggestions, which greatly improved the quality of this work. My heartfelt thanks go to the program coordinator Dr. Hari Bahadur Darlami and to the faculty and staff of the Department of Mechanical and Aerospace Engineering, Pulchowk Campus, for providing a supportive academic environment and the necessary resources to carry out this research.

I would like to extend my sincere appreciation to Mr. Ram Krishna Deupala and Mr. Anil Duwal for granting permission and providing essential support for data collection. Their cooperation and assistance were crucial to the successful completion of this research.

I am especially grateful to my friend Binod KC for his valuable assistance with data collection, as well as for his help with proofreading and technical support throughout the research process. I am deeply grateful to my family and friends (080-MSREE-Batch) for their constant support, understanding, and motivation during this journey. Their encouragement gave me the strength to persevere through challenges.

Finally, I acknowledge everyone who directly or indirectly contributed to the completion of this thesis. This work would not have been possible without their support.

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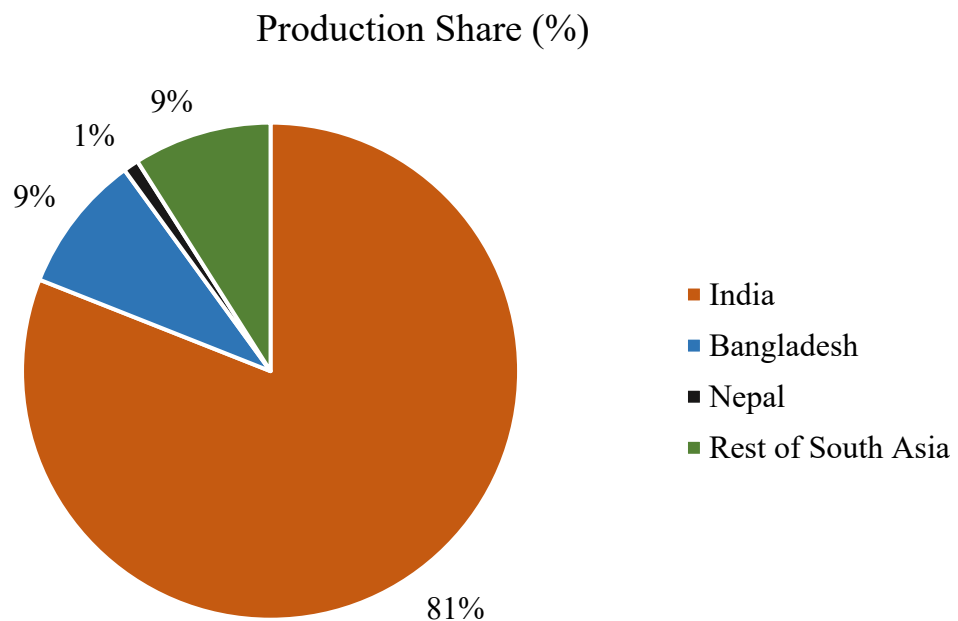
CO	Carbon monoxide
GW	Giga watt
IRR	Internal Rate of Return
LTS	Long-term strategy
NDC	Nationally determined contribution
BAU	Business as usual
CCAC	Climate and Clean Air Coalition
CH ₄	Methane
CO ₂	Carbon dioxide
DPP	Discounted payback period
FCBTK	Fixed chimney bull's trench kiln
GHG	Greenhouse gases
ICIMOD	International Center for Integrated Mountain Development
Kcal	Kilo calories
KWh	Kilowatt hour
MCBTK	Mobile chimney kiln
MW	Mega watt
NEA	Nepal electricity authority
NOC	Nepal oil corporation

NO _x	Nitrogen oxides
NPR	Nepalese rupees
NPV	Net present value
PJ	Peta joule
PM	Particulate matter
SEC	Specific energy consumption
SO ₂	Sulfur dioxide
VSBK	Vertical shaft brick kiln
WECS	Water and Energy Commission Secretariat
IPCC	Intergovernmental Panel on Climate Change
CFD	Computational Fluid Dynamics

CHAPTER ONE: INTRODUCTION

1.1 Background

Brick production contributes to construction activity and broader economic growth in Nepal and other South Asian countries. It remains a preferred building material because its cost is relatively low, the required raw materials are available locally. Over the past few decades, growth in population, expansion of urban areas, and rising demand for buildings and infrastructure have increased the scale of brick production. Even so, the sector is also considered one of the energy demanding and environmentally harmful small and medium scale industries in the region (ICIMOD, 2019).



(Source: World Bank (2020))

Figure 1.1: Brick production trend in south asia

As illustrated in Figure 1.1, brick production in South Asia is heavily concentrated in India, which accounts for about 81% of total regional output. Bangladesh contributes approximately 9% whereas Nepal represents only about 1% of the total brick production in South Asia. The remaining 9% is shared by other countries in the region. The Nepal's brick production is relatively low compared to its neighbors and is highly dominated by India (World Bank, 2020).

The brick making industry still uses predominantly coal fired kilns in Nepal and is a large user of fossil fuel. The conventional brick kiln technologies such as Fixed Chimney Bull's Trench Kiln (FCBTKs) have traditionally dominated the brick production in the country. These systems are often associated with waste of fuel, ineffective regulation of combustion and increased air pollution. In response to growing worries on energy demand and environmental pollution efforts have been made to gradually introduce more efficient and eco-friendly technologies like Vertical Shaft Brick Kilns (VSBKs) and tunnel kilns in the brick industry sector in Nepal (Pole, 2012).

The tunnel kilns are considered one of the latest technologies in brick production. They are operated continuously and the bricks are moved continuously through preheat, firing and cool zones with the heat source stationary. This ongoing cycle creates better temperature control more uniform brick quality and allows for greater recovery and utilization of heat throughout the kiln zones. In South Asia (Bricks-SEA, 2015), the tunnel kilns are sometimes considered a relatively energy-efficient and environmentally friendly method of making bricks on a large scale.

It is not always possible to obtain high efficiency in the real operating condition of a tunnel kiln although it has some technological benefits. The actual performance they achieve is significantly affected by the quality of their design, operation and maintenance practices. Based on experience in Nepal and neighboring countries, these kilns can be less efficient than they were designed to be due to a number of reasons including incorrect operation, excess air intake, heat losses, poor insulation and inadequate monitoring and control. This can lead to unnecessary usage of fuel and ultimately higher operating cost and unnecessary emissions (WECS, 2020).

The brick industry is one of the major sources of air pollution and greenhouse gas emissions. Pollutants of CO₂, CO, PM, SO₂ and NO_x are discharged from coal and other fuels used in brick kilns and they are harmful for environmental conditions and public health. The emissions from the kilns help to lower air quality, increase health hazards and the global concern of climate change. Brick kilns are known to be a significant source of urban air pollution in the Kathmandu Valley in previous studies conducted in Nepal (Department of Environment, 2022). Thus, the environmentally sustainable development of this industry has become a nation's priority. This is also evident from

the estimation by ICIMOD (2019) that around 5.1 million tons of CO₂ are emitted every year from the brick industry in Nepal.

The brick industry is significant and some national and international initiatives have promoted the use of cleaner and efficient brick making methods in Nepal. According to the Roadmap for Efficient Brick Production in Nepal the key avenues of sustainable development of brick sector are: modernization of the kiln, energy efficiency and emissions reduction (Pole, 2012). The recent research on Kiln technology, emission assessment and cleaner production option in Nepal indicated that under appropriate conditions, advanced kiln technology like tunnel kilns can minimize fuel consumption and emissions in the production of pottery. Overall, the use of coal equivalent in the brick industry is estimated at around 465,220 tons per year, further emphasizing the significance of enhancing energy performance in this sector (Thakuri et al., 2024).

As per the NDC 3.0, Nepal under the Paris Agreement, industrial energy efficiency and emission reduction is one of the key components of its climate mitigation strategy. The brick industry does not have specific Clean Air Plans, but there are programs to improve the energy efficiency of the bricks industry and to cut emissions which are closely related to Nepal's overall environmental and climate policy goals.

The evaluation of tunnel kiln performance first requires understanding how energy is used in the system and where the main losses occur. Specific Energy Consumption (SEC) defined as the energy used per unit of brick production is widely applied as an important indicator of kiln efficiency. Also, international assessment frameworks for brick kilns emphasize detailed energy audits, mass and energy balance analysis, and emission measurement as essential methods for detecting inefficiencies and identifying opportunities for improvement (Climate and Clean Air Coalition, 2016).

Water and Energy Commission Secretariat (WECS) of Nepal has released the Energy Audit Guidelines for Industrial Sectors to encourage standardization in energy audit of industrial system. The guidelines offer practical approaches to gathering data, analyzing energy flows and identifying opportunities for energy conservation, which can also be applied in tunnel brick kiln operations (WECS, 2020). Most of the brick kilns in Nepal even tunnel type still operates with no formal energy audit and systematic performance assessment.

The situation underlines the need to assess the performance of an operating tunnel brick kiln in Nepal focusing on energy consumption, emission, and financial aspects through a field-based approach. Such an assessment can serve as baseline information on how the kiln is being used can identify the primary energy loss areas, can measure the environmental impact and can become a basis for determining what practical steps can be taken to improve the kiln's performance in local conditions. The results can also help brick makers, policy makers and other stakeholders to make informed decisions on cleaner, efficient and sustainable brick production.

Along with field measurement this study incorporates CFD analysis and fuel-switching assessment to better understand how combustion conditions affect kiln performance. Transient CFD is well suited to tunnel brick kilns because the firing process is time-dependent, and previous studies have shown that unsteady simulations can represent variations in hot-gas temperature and thermal behavior under changing operating conditions (Ngom et al., 2021; Alonso-Romero et al., 2024). Also, fuel switching is increasingly considered a practical route toward cleaner brick production in South Asia, where coal-based kilns remain associated with high energy use, substantial carbon emissions, and severe air pollution. Earlier studies have similarly identified kiln modernization and cleaner fuel adoption as important measures for improving environmental performance (Eil et al., 2020). On this basis, the combined use of transient CFD and coal to natural gas transition analysis provides a stronger basis for evaluating possible reductions in energy use, emissions, and operating cost.

To address these needs, the thesis presents an integrated assessment of a tunnel brick kiln in Nepal covering energy, emissions, financial performance, and transient CFD analysis. The conventional techniques are employed for the study of energy efficiency, mass and energy balance analysis, emission estimation and combustion study under operating conditions. The potential benefits of moving away from coal to natural gas are also discussed. It is meant for enhancing knowledge about the performance of the tunnel kiln in Nepal and provide practical suggestions for improved energy efficiency, emission reduction and cleaner brick production.

1.2 Current scenario of the brick industry in Nepal

The brick industry in Nepal is a significant construction material industry providing bricks for urbanization, housing and other infrastructure. There are over 1200 kilns in

operation throughout the country and approximately 5 billion bricks are manufactured each year, rising during the dry season. Local economies are also benefited from the brick industry by seasonal employment and ancillary activities including clay extraction, transport and labor services. It is still far from being diversified in terms of technologies however traditional kiln technologies still enjoy a wide dominance, particularly FCBTK and MCBTK which are energy intensive and predominantly coal fired. These kilns use more energy per unit of production than is recommended by international standards because of poor insulation, poor combustion control and lack of process monitoring.

Recently, there has been increasing interest among policy makers, researchers and civil society organizations in environmental aspects of brick production. Brick kilns are known as the source of air pollutants such as particulate matter (PM10 and PM2.5), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂) and greenhouse gases (GHGs) like carbon dioxide (CO₂). Research and monitoring results including in urban areas like Kathmandu Valley have shown that emissions from brick kilns are also a significant source of air pollution and associated health impacts during the winter season when dispersion in the atmosphere is reduced. There has been a greater focus on promoting green technologies and improving environmental efficiency of the sector to align with the Nationally Determined Contributions (NDC 3.0) of Nepal and the overall objective of clean air.

These problems are better understood and large-scale application of modern and energy efficient kiln technologies in Nepal are still relatively few. The new technologies like zigzag kilns, VSBK, Hybrid Hoffman kilns (HHK) and tunnel kilns have not yet gained a significant market share compared to the traditional kiln systems. Slow progress has been made due to high initial costs, limited financing, inadequate technical expertise to operate and maintain the brick kilns and the informal sector of much of the brick-making industry. Important practices like excess air control, heat recovery and systematic energy auditing are not always employed by the plants that have installed improved kiln technology. This produces a obvious gap between the efficiency expected and the operating efficiency achieved.

The WECS Energy Audit Guidelines for Industrial Sectors are provided as a useful framework for energy auditing and improving energy performance in industrial

facilities such as brick kilns. In actual applications detailed energy audits and emission assessments are not widely used particularly for more sophisticated systems like tunnel kilns. Although reliable baseline information on actual energy use, specific energy consumption (SEC) and emission intensity of tunnel kilns in Nepal is still limited. It demonstrates the need for targeted research on their energy and emission performance for more informed decisions on cleaner and more efficient production of bricks.

The use of tunnel kiln technology in Nepal are very limited as shown in Table 1.1. The national assessment by Thakuri et al., (2024) reported that only 3 brick kilns were tunnel kilns in Nepal in 2020 while the remaining 1,236 brick kilns were of the traditional type. The old-style systems (FCBTK and zigzag kilns) are still the most prevalent and more than 80% of the kilns in operation are of this type. This small number of tunnel kilns is indicative of the technological lag in the brick industry in Nepal and also highlights the importance of detailed studies of existing tunnel kiln performance for promoting the wider adoption of this technology in the future.

Table 1.1: Brick kiln technologies in Nepal

Kiln Technology	Number of Kilns in Nepal
Straight-line FCBTK	817
Zig-zag FCBTK	263
Vertical Shaft Brick Kiln (VSBK)	25
Hoffman Kiln (HK)	6
Tunnel Kiln (TK)	3
Hybrid Hoffman Kiln (HHK)	2
Clamp kiln	114
Mobile Chimney Bull's Trench Kiln	6
Total	1,236

(Source: Thakuri et al., 2024)

1.3 Statement of the problem

Brick making is one of the industries which have energy demands high and significant impact on environment in Nepal. Brick making is needed for housing and provision of infrastructure but still is largely based on coal fired kilns which consume vast quantities of fuel and emission of major amounts of air pollution. The traditional kiln technologies are still prevailing in the industry like FCBTK and zigzag kilns and they are frequently associated with inefficient combustion, poor process control and high specific energy

consumption. The industry continues to be a significant contributor of greenhouse gases and worsening local air quality.

To improve energy efficiency, produce better quality bricks, and reduce emissions tunnel kiln technology has been introduced in Nepal in recent years. The national surveys show that, among the more than 1,200 brick kilns operating in the country, only three are tunnel kilns which is less than 0.3% of the total. This shows that tunnel kiln technology is still only beginning in Nepal.

The tunnel kilns are a cleaner and more efficient option. The available studies have dealt mainly with traditional kiln systems while data on tunnel kiln energy use, specific energy consumption, heat loss distribution, and actual emission levels are still lacking. Their field performance can be affected by factors such as excess air supply, air leakage, fuel characteristics, insulation quality and the effectiveness of process control. Without detailed measurements and proper analysis, it is therefore difficult to judge whether tunnel kilns in Nepal are really performing as efficiently as expected.

Brick kilns emissions are another serious environmental challenge in Nepal. The brick sector is a major source of pollutants including particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen oxides (NO_x) and carbon dioxide (CO₂). The tunnel kilns are generally regarded as cleaner than conventional kiln systems but measured emission data from operating tunnel kilns in Nepal are still limited. This helps policy makers and industry stakeholders who still lack the base line information to evaluate the real benefits of tunnel kiln technology and to plan effective measures for cleaner brick production.

The combustion process and the thermal conditions inside tunnel kilns are complex and cannot be described by field measurements alone about kiln. Because of the time dependent heat transfer and combustion behavior, the kiln performance will be influenced, so transient CFD analysis can be used to study temperature distribution and combustion characteristics under changing operating conditions. The continued use of coal in Nepalese brick kilns raises the question of whether cleaner fuels like natural gas could cut energy use, emissions and operating costs. Therefore, a comprehensive study that combines field measurement, emission estimation, financial analysis, transient CFD simulation and fuel switching assessment for tunnel brick kilns in Nepal is still absent.

The research is focused to address the current lack of comprehensive assessment of tunnel brick kiln performance in Nepal. The assessment gives the importance to energy use, emissions, financial feasibility, combustion characteristics and the possibility of shifting to cleaner fuels. This assessment helps to identify the main causes of inefficiency, quantify the environmental impacts, judge the economic viability and recommend practical measures for cleaner and more efficient kiln operation. Limited evidence continues to constrain efforts to improve tunnel kiln performance and support the wider modernization of Nepal's brick industry.

1.4 Objectives

1.4.1 Main objective

- To evaluate the energy, emissions, financial, and combustion performance of a tunnel brick kiln and the potential of natural gas replacement

1.4.2 Specific objectives

The specific objectives of this research are

- To determine the SEC of the tunnel kiln and calculate its thermal efficiency using direct and indirect methods
- To evaluate the financial viability of different brick production scenarios using financial metrics
- To estimate tunnel kiln CO₂ emissions and emission intensity using stack gas and fuel-based methods
- To develop a transient CFD model of a tunnel brick kiln for local optimization under different combustion conditions
- To evaluate the thermal, emission, and economic performance of replacing coal with natural gas in the tunnel brick kiln

1.5 Limitation of the study

Although this research aims to conduct a comprehensive energy, financial, and emission analysis of a tunnel brick kiln in Nepal, certain limitations exist:

- The study is limited to a single tunnel brick kiln and may not represent all kilns
- Results depend on the accuracy of operational and production data provided by the kiln

- Emission analysis mainly relies on fuel-based CO₂ estimation rather than comprehensive on-site pollutant measurements
- Seasonal and operational variations are not fully captured
- Financial analysis is based on current assumptions and may change with market conditions
- The CFD analysis was conducted on a representative section of the kiln under selected combustion conditions, and therefore may not represent the full complexity of plant-scale operation

CHAPTER TWO: LITERATURE REVIEW

2.1 Energy situation of Nepal

Energy resources are generally classified into two main categories: renewable and non-renewable. Renewable energy is derived from naturally replenishing sources that are virtually inexhaustible in the long term, although their rate of availability may be limited. Non-renewable energy, by contrast, is obtained from finite resources that diminish with continued consumption. The relationship between economic sectors and energy types is presented in Figure 2.1.

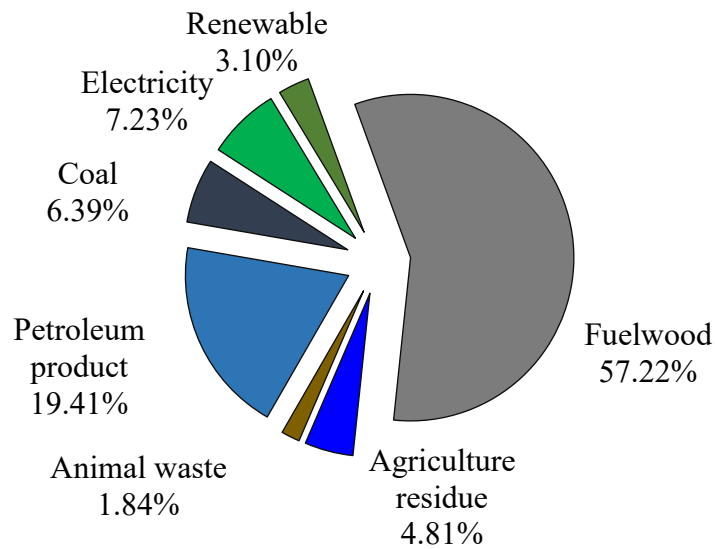
Reserve/production (R/P) ratio is used to determine how long an energy source is going

Energy/Economic Sectors	Types of Energy
<ul style="list-style-type: none">• Residential/domestic sector• Industrial sector• Commercial sector• Agricultural sector• Transport sector• Construstion and mining sector	<ul style="list-style-type: none">• Renewable Energy<ul style="list-style-type: none">• Conventional (Hydro, Biomass etc.)• Modern (solar, wind etc.)• Non- renewable Energy<ul style="list-style-type: none">• Traditional energy (wood, dung cake, Agriculture residue etc.)• Fossil fuels (Petrol, Diesel, Coal etc.)• Natural gas

Figure 2.1: Economic sector and type of energy

to last with present technology at current rate.

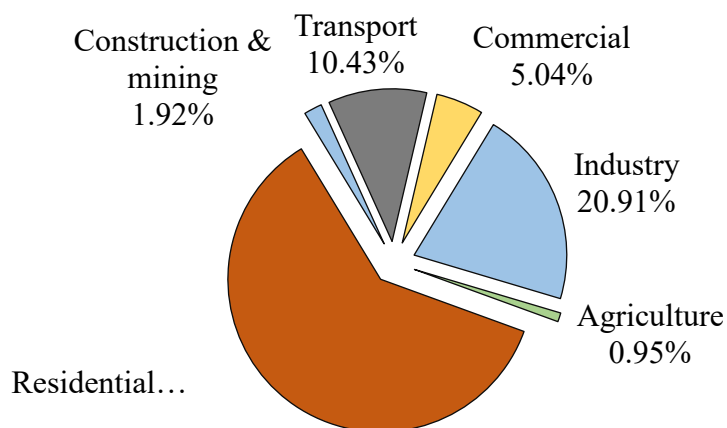
In 2023, Nepal's total energy consumption was 532.42 PJ, which was 16.81% lower than the 640 PJ reported for 2022. Owing to the absence of domestic petroleum resources and the limited availability of coal reserves, biomass continues to dominate the national energy mix, with firewood contributing 57.22% of total energy consumption. Petroleum products account for the next largest share at 19.41%, followed by electricity (7.23%), coal (6.39%), agricultural residue (4.81%), renewable energy (3.10%), and animal waste (1.84%). The overall fuel-wise distribution of energy consumption in Nepal is shown in Figure 2.2.



(Source: WECS, 2024)

Figure 2.2: Share of fuels in energy consumption

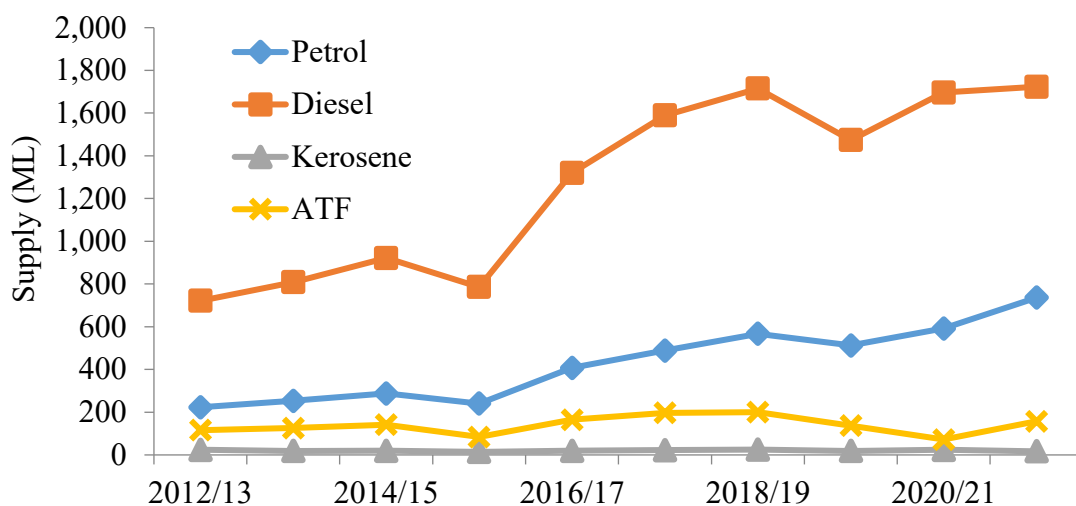
As the country modernizes and commercial and industrial activities become more mechanized, energy consumption has increased notably in the commercial, industrial, and transport sectors, whereas the share used by the residential sector has shown a declining trend. In 2022, the residential sector accounted for 60.75% of total energy use, followed by the industrial sector at 20.91%, transport at 10.43%, commercial activities at 5.04%, and other sectors at 2.87%, as illustrated in Figure 2.3.



(Source: WECS, 2024)

Figure 2.3: Sectoral energy consumption

The supply pattern of petroleum products in Nepal is depicted in Figure 2.4. Over the years, there has been a steady growth in the supply of diesel, petrol, and aviation turbine fuel (ATF) with annual increases of 9.10%, 12.68%, and 3.09%, respectively. Diesel remains the most extensively consumed petroleum product each fiscal year, owing to its wide usage in infrastructure development, heavy equipment, freight vehicles, agriculture, and industries. On the other hand, kerosene is currently undergoing a phase-out process, leading to an annual decrease of 3.22% in its consumption.



(Source: NOC, 2023)

Figure 2.4: Supply of petroleum product

2.2 Industries in Nepal

As of fiscal year 2022, Nepal had 3,280 registered manufacturing industries. Figure 2.5 presents their distribution by category. The largest share consists of textiles, readymade garments, and leather-based industries, followed by food, beverage, and tobacco industries. Chemical products, rubber, glass, and plastics-based industries occupy the third position, whereas cement, brick, concrete, and clay-based industries form the fourth-largest category.

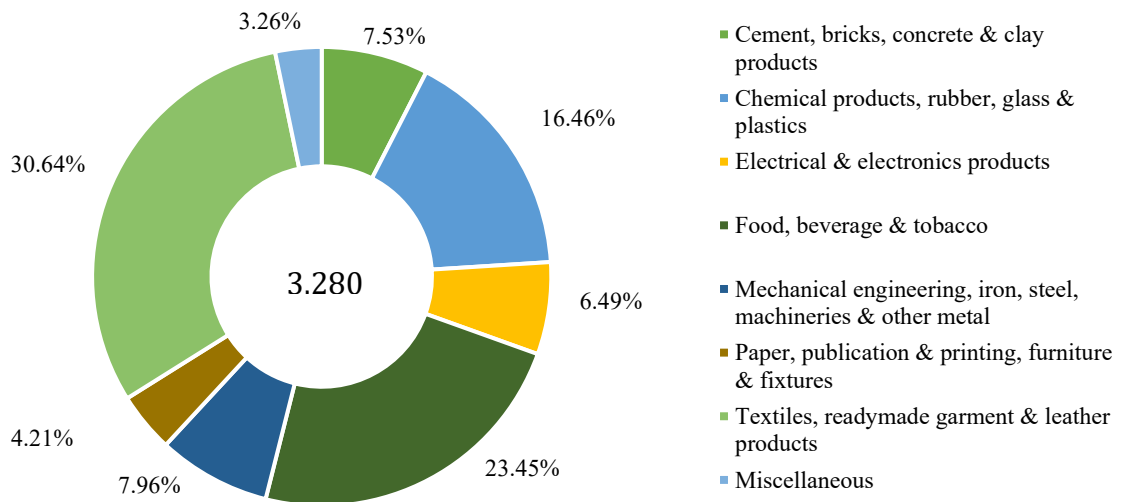
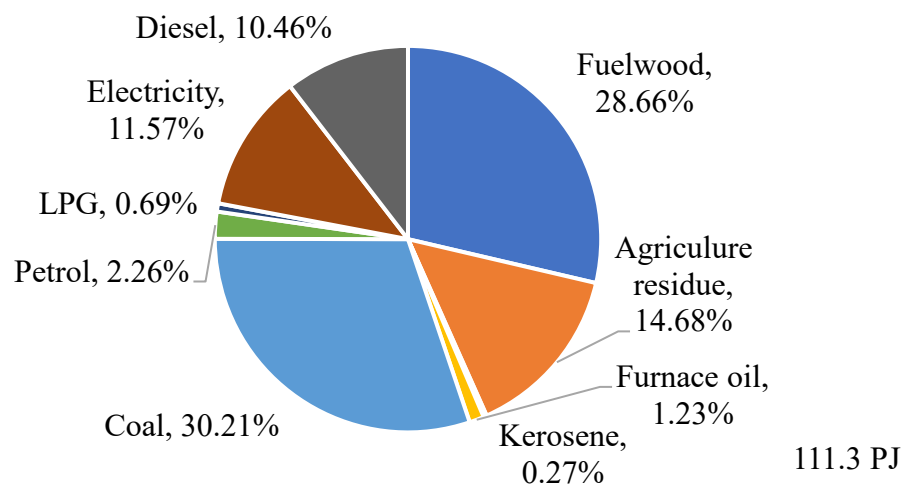


Figure 2.5: Industries in Nepal by category

2.3 Energy use in industrial sector

Coal and fuelwood constitute the major sources of energy consumed in Nepal's industrial sector, followed by agricultural residue, electricity, and diesel. In 2023, the sector's total energy consumption was 111.3 PJ. Coal contributed the highest share of this total at 30.21%, while fuelwood and electricity accounted for 28.66% and 11.57%, respectively. The Figure 2.6 presents the overall distribution of energy consumption in the industrial sector by fuel type of Nepal.



(Source: WECS, 2024)

Figure 2.6 Energy consumption in Industrial sector by fuel type

The Water and Energy Commission Secretariat (WECS) forecasted future energy and electricity demand in Nepal’s industrial sector using a scenario-based framework. The results show that by 2050, industrial energy demand under the business-as-usual scenario is projected to reach 261.9 PJ, 582.8 PJ, and 1210.9 PJ under the low-, medium, and high growth cases, respectively. Under the medium growth electrification scenario, the corresponding energy demand is projected at 420.9 PJ. The details of the projected energy and electricity demand across these scenarios are provided in Table 2.1.

Table 2.1: Energy and electricity growth in different scenarios

Scenarios	2025	2030	2035	2040	2050
Total Energy Demand in PJ					
Low Growth Scenario (BAU)	117.4	135.3	154.8	184.9	261.9
Medium Growth Scenario (BAU)	126.7	164.3	216.8	305.4	582.8
Medium Growth (Electrification Scenario)	127.1	161.3	207.4	269.7	420.9
High Growth Scenario (BAU)	134.6	195.9	309.9	500.4	1,210.9
Total Electricity Demand in GWh					
Low Growth Scenario (BAU)	5,756	10,045	16,001	21,306	36,985
Medium Growth Scenario (BAU)	6,179	12,099	22,159	34,689	80,658
Medium Growth (Electrification Scenario)	5,650	11,893	22,613	41,100	116,925
High Growth Scenario (BAU)	6,565	14,421	31,677	56,836	167,588

(Source: WECS, 2023)

2.4 Structural and Brick clay product industry

Brick manufacturing is a labor and energy intensive activity and its specific energy consumption varies with the kiln technology. The sector needs a lot of fuel input and energy expenditure is about 30.64% of the total production cost. In Nepal, the main fuel used in brick industries is coal but small quantities of saw dust and firewood are also used. The coal cannot be considered a clean energy source due to its contribution to greenhouse gas emissions and other environmental impacts. The specific energy consumption of the brick industry is shown in Table 2.2.

Table 2.2: SEC in the structural and brick clay product industry

Particular	Electrical (kWh/MT)	Thermal (GJ/MT)
Brick industries		
WECS, 2019/20	2.57	0.95
WECS, 2024/25	5	0.72
India	-	0.95-1.82

(Source: WECS 2024)

The Table 2.2 indicates that, the electrical energy consumption of the brick industry is 5 kWh/MT, while thermal energy consumption is 0.72 GJ/MT. Compared to the 2019/20 values, electrical energy intensity went up by about 95% and thermal energy intensity fell by roughly 24% showing a significant shift towards higher consumption of electricity and lower demand for thermal energy. Since these values are based on energy audits in a limited number of industries, they should be interpreted with caution and should not be considered completely representative of the actual energy consumption pattern in the entire brick sector.

2.5 Consumption of fuel in the brick industry

The production of brick is energy intensive because of the high temperatures involved in drying and firing. The firing is usually from 900°C to 1,050°C. Similarly, studies on bricks made from clay of Kathmandu Valley reported optimum firing temperature of 900–1050°C (Chapagain et al., 2020; N. Bohara et al., 2020). Coal is still the main fuel

for brick kilns in South Asia, including Nepal, due to its high calorific value and relatively stable combustion properties (World Bank, 2020).

As per the World Bank (2020), South Asia produces around 300–310 billion bricks annually and the brick sector consumes a considerable portion of industrial coal. It is estimated that Nepal’s brick industry consumes several hundred thousand tons of coal annually and it is one of the major coal consuming industrial sectors in the country (Thakuri et al., 2024).

The fuel consumption depends heavily on the kiln technology. The Traditional FCBTK generally consume around 140–180 kg of coal per 1,000 bricks produced, which is equivalent to a specific energy consumption of roughly 1,800–2,400 MJ per 1,000 bricks (World Bank, 2020; CCAC, 2016). The improved zigzag kilns usually have better combustion efficiency and lower heat losses, consuming about 100–140 kg of coal per 1,000 bricks, with corresponding SEC values in the range of 1,400–1,800 MJ per 1,000 bricks (CCAC, 2016).

The advanced kiln technologies show even better improvement of fuel efficiency. The VSBK typically use about 80-110 kg of coal per 1,000 bricks, which translates into SEC values of about 1,100-1,500 MJ per 1,000 bricks (World Bank, 2020). Hoffman kilns also consume relatively less fuel. Typical coal consumption is in the range of 90-120 kg per 1,000 bricks. The tunnel kilns generally show the lowest fuel demand because of their continuous mode of operation, with coal consumption usually ranging from 70 to 100 kg per 1,000 bricks and SEC values of about 1,000–1,400 MJ per 1,000 bricks, depending on operational efficiency and insulation quality (CCAC, 2016; Thakuri et al., 2024).

The research by Thakuri et al. (2024) reported that improvements in energy efficiency through cleaner kiln technologies can reduce coal consumption by about 15–30% compared with traditional kilns for Nepal.

2.6 Production process flow diagram for tunnel brick kiln

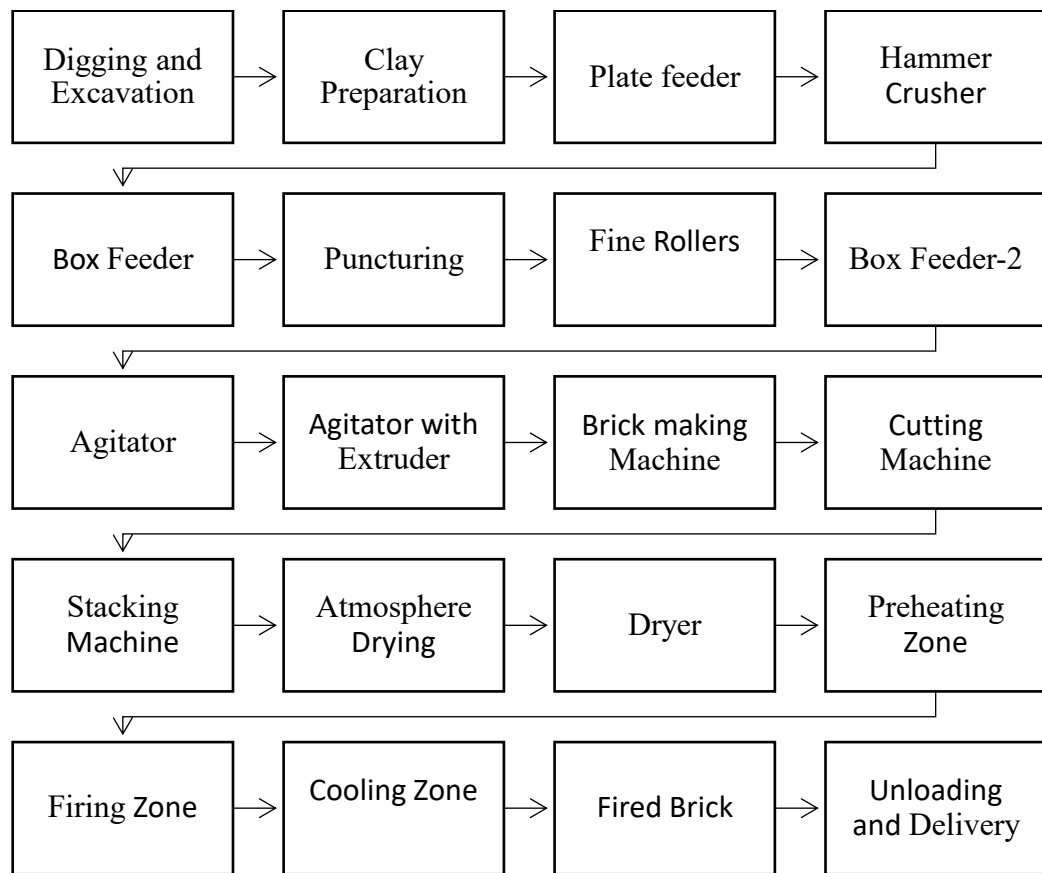


Figure 2.7: Production process flow diagram for tunnel brick kiln

The Figure 2.7 shows the complete brick manufacturing sequence in a tunnel brick kiln from raw material extraction to the unloading of fired bricks. The process begins with clay excavation, followed by clay preparation in which stones and other impurities are removed. The clay is mixed with sand or other soil materials depending on the required composition, The prepared material is then delivered to a plate feeder, which controls the continuous feeding of clay in line with production demand.

The plate feeder feeds the material to a hammer crusher. The large lumps of clay are broken into smaller particles to get better uniformity and workability. The crushed clay is then stored and supplied via a box feeder and it may have an aging period of about three days. This aging process enhances the plasticity and molding qualities of the clay before the next stage of processing. Then the material passes through a puncturing unit that helps break down the last remaining lumps and prepares the clay for fine grinding.

The conditioned material is passed through a fine roller which reduces the particle size to about 2 mm giving a uniform and fine texture. The material is then proportioned out by two box feeders one for soil and one for coal at a soil to coal ratio of 10:1 by volume. The internal mixture of coal is used as an additional fuel during firing to improve the combustion efficiency. The proportioned mix is then transferred to an agitator where complete mixing is affected and water at about 16% added to give suitable plasticity.

The homogenized mixture is then fed to the brick making machine or extruder which shapes it into a continuous clay column. The column is then cut into individual green bricks of standard size, $240 \times 115 \times 60$ mm, each weighing about 3–4 kg. The green bricks are then laid in layers by a stacking machine and loaded on kiln cars for drying. The first drying is carried out under atmospheric conditions and the moisture content is decreased to about 10%. Then the bricks are sent to a dryer where moisture is decreased further to below 2% before the firing zone. Proper drying is important to avoid cracking and structural damage during exposure to high firing temperatures.

Following the drying zone, the bricks enter the tunnel kiln and go through three temperature zones in order. In the preheating zone the temperature steadily increases from about 350°C to 650°C eliminating any remaining moisture and assisting in the prevention of thermal shock. After that the bricks enter the firing zone, where vitrification and the development of mechanical strength typically take place at temperatures between 650°C and 930°C. The bricks then go through the cooling zone, where the temperature is carefully lowered from the fire level to about 60°C to avoid cracking. The manufacturing process is finished when the burnt bricks are cooled, unloaded, and ready for distribution. Additionally, disciplined operation and appropriate maintenance practices can boost overall productivity and help achieve ambient-air benefits (Chen et al.,2017).

2.7 Study on the financial parameters of brick kilns

The brick kilns' long-term viability and the viability of a technological shift are significantly influenced by their financial success. A significant investment in site development, kiln construction, mechanical and electrical equipment, drying and firing systems, and working capital is required for the energy-dependent and capital-intensive industrial activity of brick making. Due to high fuel consumption, fluctuating coal prices, seasonal production cycles, and stricter environmental laws, the brick industry

in South Asia especially Nepal continues to be financially risky (World Bank, 2020; CCAC, 2016).

Each kiln technology has a different capital investment. While advanced continuous systems like tunnel kilns require significantly higher investment, often in the range of USD 1,000,000 or more depending on plant capacity and the degree of mechanization, traditional FCBTK typically involve relatively low upfront costs, typically around USD 50,000–80,000 (Bricks-SEA, 2012). Automated feeding systems, better insulation, continuous firing chambers, and material handling equipment are the primary causes of tunnel kilns' greater capital requirements. Better energy efficiency and more consistent manufacturing can boost long-term financial success despite this high initial cost (Thakuri et al., 2024).

Both variable and fixed expenditures make up the brick kiln's operational expenses. While fixed expenses typically include depreciation, administration, and interest payments, variable costs include coal, energy, labor compensation, raw materials, and maintenance. In typical kilns, fuel costs alone can make up between 50 and 60 percent of overall operating costs (World Bank, 2020). Due to Nepal's reliance on imported coal, financial performance is especially vulnerable to fluctuations in global fuel costs (WECS, 2010). Long-term cost savings can be achieved by reducing coal use by roughly 15–30% through improved kiln technology (Thakuri et al., 2024).

Indicators like Internal Rate of Return (IRR), Net Present Value (NPV) and Payback Period are frequently used to assess the financial feasibility of brick kiln projects. The studies from South Asia show that when fuel savings and quality improvements are made, modernizing brick kilns can produce appealing financial returns. The project level evaluations in Bangladesh reported a Financial IRR (FIRR) of 27–34% for improved kiln technologies, with payback periods in the range of 3–4 years (ADB, 2013). The bankability assessment in Nepal estimated payback periods of around 2.9 years for FCBTKs, 2.9 years for zigzag kilns, and approximately 3.6 years for tunnel kilns, depending on operational conditions and financing structure (ICIMOD, 2021). In some cases, retrofit projects especially zigzag conversions, have achieved even shorter payback periods of less than 1–2 years because of lower coal consumption (CSE, 2018).

According to Bricks-SEA technical assessments the investments in tunnel kiln may recover their initial cost within about two years under favorable operating conditions,

particularly when capacity utilization remains high and brick prices are stable. The overall financial performance is still sensitive to changes in fuel price, production volume, selling price, and interest rate. Hence, sensitivity analysis is important for evaluating financial risk and long-term viability.

Overall, despite the substantially higher capital requirement of advanced technologies such as tunnel kilns compared with traditional kilns, the literature suggests that better energy efficiency, lower specific fuel consumption, improved brick quality, and fewer rejected products can result in competitive IRR values, typically above 20% in well-managed projects, together with acceptable payback periods of around 2–4 years. Hence, a comprehensive financial assessment is essential to determine whether modernization of brick kilns, especially through tunnel kiln adoption, is economically feasible under Nepalese operating conditions.

2.8 Emission situation of Nepal

Nepal has committed to achieving net-zero emissions by 2045. However, in 2019, greenhouse gas emissions from the energy sector were estimated at 17.18 MtCO₂-eq, as shown in Table 2.3. The residential sector contributed the largest share of these emissions, followed by the transport and industrial sectors. The transport sector alone accounted for 4.49 MtCO₂-eq. Therefore, expanding electrification in transport could significantly help reduce overall greenhouse gas emissions in Nepal.

Table 2.3: Emission from energy sector in Nepal (million metric tonnes)

Sectors	Methane (CH ₄)	Nitrous oxide (N ₂ O)	Carbon dioxide (CO ₂)	CO ₂ Equivalent
Residential	0.41	3.57	2.09	6.07
Transport	0.40	0.01	4.73	5.15
Industrial	0.02	0.02	4.45	4.49
Commercial	0.01	0.13	0.54	0.69
Agricultural	0.00	0.00	0.78	0.78

Sectors	Methane (CH ₄)	Nitrous oxide (N ₂ O)	Carbon dioxide (CO ₂)	CO ₂ Equivalent
Total	0.85	3.74	12.59	17.18

(Source: LTS, 2021)

The fuel-specific emission factors show how much pollution is released for every unit of energy produced during combustion and are typically stated in kg/TJ. For a number of fuels, including coal, natural gas, crude oil, wood, industrial waste, and charcoal, the emission factors for NO_x, CO, CO₂, and CH₄ are listed in Table 2.4.

The data show that coal has comparatively high NO_x and CO₂ emission factors which makes it an important source of greenhouse gas emissions. The industrial waste has the highest CO₂ emission factor while charcoal is characterized by high CH₄ emissions. The natural gas produces lower NO_x and CO₂ emissions than coal. Such emission factors are useful for estimating total emissions in industrial applications including brick kilns.

Table 2.4: Emission factors of different fuels

Fuel type	Emission factor (in kg/TJ)			
	NO _x	CO	CO ₂	CH ₄
Coking coal	300	150	94600	10
Coal	300	150	96100	10
Natural Gas	53	2000	56100	1
Crude oil	200	4000	73300	3
Kerosene	167	15	71900	3
Wood	100	2000	112000	30

Fuel type	Emission factor (in kg/TJ)			
	NO _x	CO	CO ₂	CH ₄
Industrial wastes	100	4000	143000	30
Charcoal	100	4000	112000	200

(Source: ABC, Emission Inventory Manual)

2.9 Environmental impact of the brick industry

Brick making in Nepal is highly dependent on coal and causes serious environmental harm through emissions from coal burning and the extraction of raw materials. The brick industry is considered as one of the major sources of seasonal air pollution especially in the urban areas like Kathmandu Valley. Coal combustion in brick kilns releases pollutants such as particulate matter (PM_{2.5} and PM₁₀), black carbon (BC), sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO₂) which are detrimental to air quality and human health (DoEnv, 2022). Studies have also identified brick kilns as a major source of fine particulate pollution during winter months (World Bank, 2020).

The brick industry is also a big source of greenhouse gas emissions. A national study of the Nepalese brick industry found that nearly 1,236 kilns operating in 41 districts released about 1.30 million tons of CO₂-equivalent each year (Thakuri et al., 2024). The sector has a lot of carbon emissions because it uses a lot of coal as its main fuel and traditional kiln technologies don't burn coal very well. Black carbon emissions are of particular concern because they contribute both to climate warming and to the formation of regional atmospheric brown clouds over South Asia (World Bank, 2020).

The brick production also contributes to environmental degradation through the extraction of clay and fertile topsoil. Unregulated topsoil removal for brick manufacturing can reduce agricultural productivity and lead to land degradation and erosion (ICIMOD, 2021). The dust produced during excavation, crushing, and material handling further contributes to localized pollution. The regions where biomass is used as fuel for brick production may also indirectly increase pressure on forest resources.

Table 2.5: GHG emissions from brick kilns in Nepal

Technology	Number	Coal Consumption (ton)	CO ₂ (ton)	CH ₄ (ton)	N ₂ O (ton)	CO ₂ -Eq (ton)
Straight-line FCBTK (natural draft)	817	330,644	916,711	96.9	14.5	923,276
Zig-zag FCBTK (natural draft)	263	77,487	214,332	22.7	3.4	216,370
VSBK	25	5,714	15,842	1.7	0.3	15,956
Hoffman kiln	6	10,624	29,455	3.1	0.5	29,666
Tunnel kiln	3	7,139	19,793	2.1	0.3	19,935
HHK	2	2,266	6,282	0.7	0.1	6,327
Clamp kiln	114	27,386	75,929	8.0	1.2	76,473
MCBTK	6	3,962	10,984	1.2	0.2	11,063
Total	1,236	465,222	1,289,823	136	20	1,299,065

(Source: Thakuri et al., 2024)

The Table 2.5 shows the greenhouse gas (GHG) emissions linked to the different brick kiln technologies operating in Nepal. The total about 1,236 brick kilns consumes approximately 465,222 tons of coal each year and emit about 1.30 million tons of CO₂-equivalent. The straight line FCBTKs under natural draft conditions contribute the largest share of these emissions because they are the more in number (817 units) and consume a substantial amount of coal. The zig-zag kilns exhibit relatively lower emissions, while advanced technologies such as tunnel kilns and VSBKs account for much smaller overall emissions owing to their limited number and improved combustion efficiency. The table highlights the strong association between kiln technology, coal use, and GHG emissions in Nepal's brick sector (Thakuri et al., 2024).

2.10 Performance indicators of brick kiln technology

The Table 2.6 shows a comparison of the major energy performance indicators of brick kiln technologies operating in Nepal and other parts of the world. The SEC is widely used as a key measure for assessing the energy performance of these brick kilns.

The international studies represent the traditional clamp kilns exhibit the highest energy consumption typically about 3–5 MJ/kg of fired bricks owing to poor combustion efficiency and large heat losses. The improved technologies such as Bull's Trench Kilns and Hoffman kilns generally fall within the range of 1.0–1.6 MJ/kg of fired bricks. The

more efficient systems particularly VSBKs, achieve lower SEC values of around 0.7–0.9 MJ/kg of fired bricks because of improved combustion control and better heat recovery. The modern tunnel kilns usually operate in the range of 1.3–1.8 MJ/kg of fired bricks, depending on fuel characteristics and operating conditions. These values demonstrate the potential for significant energy savings through the adoption of advanced kiln technologies (Hasanbeigi et al., 2013; Zhang et al., 2016; Madlool et al., 2011).

Table 2.6: Performance parameters of brick kiln technologies

Kiln Technology	Specific Energy Consumption (MJ/kg fired bricks)	Estimated Coal Consumption (kg/1000 bricks)	Energy Performance Level
Clamp Kiln	3.0 – 5.0	300 – 450	Very Low
MCBTK	1.4 – 1.8	180 – 280	Low
FCBTK	1.1 – 1.6	150 – 230	Moderate
Hoffman Kiln	1.0 – 1.5	150 – 220	Moderate
VSBK	0.7 – 0.9	90 – 130	High
Tunnel Kiln	1.3 – 1.8	160 – 260	Moderate-High

(Source: Hasanbeigi et al., 2013; Zhang et al., 2016; Madlool et al., 2011)

2.11 Emission profile of brick kilns in Nepal

Pollutants like particulate matter (PM_{2.5} and PM₁₀), black carbon (BC), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂) and greenhouse gases like carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are used to measure the emissions of brick kilns in Nepal. Most of these emissions come from burning coal during brick firing and the design of the kiln how well it burns, the type of fuel used, and how it is controlled all have a big effect on them.

The conventional kiln technologies particularly FCBTKs and clamp kilns tend to generate relatively high particulate emissions due to inefficient combustion and weak airflow control. The studies in Nepal have shown that brick kilns are major contributors to seasonal air pollution, especially in the Kathmandu Valley (Department of Environment [DoEnv], 2022). The particulate matter and black carbon emissions are of special concern because they adversely affect air quality and also contribute to climate warming. Nepal’s brick sector emits approximately 1.30 million tons of CO₂-equivalent annually from 1,236 kilns (Thakuri et al., 2024).

The emission performance is commonly expressed through intensity indicators such as kg CO₂ per ton of brick produced or mg/Nm³ of particulate matter in flue gas. The improved kiln technologies can lower particulate emissions by approximately 20–40% relative to traditional kilns, depending on operating control and maintenance conditions (Climate and Clean Air Coalition [CCAC], 2016). The tunnel kilns usually show lower emission variability and better combustion efficiency resulting in reduced pollutant emissions per unit of brick produced.

The emissions from Nepal's brick sector depend largely on kiln technology, coal use, and operating practice. For this reason, the adoption of cleaner and more energy efficient technologies is important for reducing local air pollutants as well as greenhouse gas emissions, thereby supporting Nepal's broader air quality and climate mitigation objectives.

2.12 Role of brick kiln emissions in Nepal's NDC 3.0

The Nepal's updated NDC 3.0 sets quantitative targets for reducing greenhouse gas emissions and supporting to a low carbon development path. The Nepal has committed to reaching net-zero greenhouse gas emissions by 2045 and to limiting total annual emissions to approximately 24.5 MtCO₂-eq by 2030 compared with projected business-as-usual (BAU) levels (Government of Nepal, 2021). The NDC 3.0 highlights the need to increase the share of clean energy, improve energy efficiency across industrial sectors, and reduce short-lived climate pollutants such as black carbon.

The brick industry is especially relevant to achieve these targets because it is one of the most coal intensive industrial sectors in Nepal. The brick sector emits approximately 1.30 million tons of CO₂-equivalent annually, largely due to coal combustion in traditional kilns (Thakuri et al., 2024). Considering the magnitude of these emissions, modernization of brick kilns can play an important role in supporting national mitigation efforts. The NDC 3.0 framework identifies improvements in industrial energy efficiency as a key mitigation measure by aiming to reduce fossil fuel dependence and promote cleaner production technologies (Government of Nepal, 2021).

The improved kiln technologies including zigzag kilns, VSBKs, and tunnel kilns, can reduce coal consumption by approximately 15–40% compared with traditional fixed-

chimney kilns (MinErgy Nepal, 2013; Climate and Clean Air Coalition [CCAC], 2016). These reductions directly contribute to lower CO₂ emissions and reduced black carbon release, which supports Nepal’s commitment to limiting short-lived climate pollutants under the NDC. The Long-Term Strategy for Net-Zero Emissions (LTS, 2021) complements NDC 3.0 by promoting low-carbon industrial development and greater energy efficiency in high emission sectors. Thus, the transition from conventional brick kilns to energy efficient tunnel kiln systems can support not only improved environmental performance but also progress toward Nepal’s quantified 2030 climate targets and its net-zero commitment for 2045.

Table 2.7: IPCC global warming potential (GWP100) values relative to CO₂

Major Greenhouse Gases	Chemical Formula	AR4 (2007)	AR5 (2013)	AR6 (2021)
Carbon dioxide	CO ₂	1	1	1
Methane – non-fossil	CH ₄	25	28	27.0
Methane – fossil	CH ₄	N/A	30	29.8
Nitrous oxide	N ₂ O	298	265	273
Nitrogen trifluoride	NF ₃	17,200	16,100	17,400
Sulfur hexafluoride	SF ₆	22,800	23,500	24,300

(Source: IPCC AR6 (2021))

The Table 2.7 presents the 100-year Global Warming Potential (GWP100) values of major greenhouse gases relative to carbon dioxide (CO₂ = 1) as reported in the IPCC Fourth (AR4), Fifth (AR5), and Sixth (AR6) Assessment Reports. The table shows how the estimated warming effects of gases like methane (CH₄), nitrous oxide (N₂O), sulphur hexafluoride (SF₆), and some hydrofluorocarbons (HFCs) have changed over time. These GWP values are used to change the amount of non-CO₂ greenhouse gases into carbon dioxide equivalent (CO₂e) for climate impact assessment.

2.13 CFD Analysis of Brick Kilns in Transient Model

The researchers are using the CFD to study how brick kilns work because it can show how flow, heat transfer, combustion, and species transport work together inside the kiln, which is hard to do with experiments. The firing process in these systems is inherently time-dependent because the temperature of the gas, the temperature of the bricks, the intensity of the combustion and the composition of the exhaust all change while the system is running. The transient CFD is a better way to look at heating history, combustion evolution, and time-dependent pollutant formation than a model that only

looks at steady-state conditions. Research on tunnel kilns has demonstrated that kiln processes are significantly time-dependent and that numerical modelling is essential for comprehending thermal dynamics, fuel efficiency, and process regulation.

The study by Alonso-Romero et al. (2024) utilized transient thermal CFD on a brick loaded kiln and evaluated various numerical methods for addressing density variation, including Boussinesq-based and ideal gas formulations. The ideal gas law method had the lowest mean relative error of 4.4%, which was better than the polynomial property method (5.0%). Their model was tested against real-world hot gas temperature data. The study also found that better insulation raised the temperature of hot gas by 12.7%. This shows that transient CFD can be used to predict temperature and also to test design changes in kilns. The study highlights that, under kiln conditions involving large temperature variations, the choice of density treatment strongly influences the accuracy of transient predictions.

The study by Alonso-Romero et al. (2025) extended this line of work by developing a transient combustion CFD model for a brick kiln to simulate a switch to natural gas. Their study combined experimental measurements from a wood fired kiln with transient combustion modeling and examined the time dependent distributions of temperature, velocity, and gaseous species under stoichiometric, fuel-rich, and excess-air conditions. The results showed that natural gas could reduce CO₂ emissions, expressed on a mole-fraction basis, by 44.08% compared with the reference case, and the study also reported transient outlet histories of CO₂, H₂O, and CO. This work is especially relevant to brick kiln research because it demonstrates that transient CFD can assess thermal behavior, combustion conditions and emission dynamics rather than being limited to the prediction of final temperature fields.

The use of unsteady simulation in brick firing also supports transient CFD work by Ngom et al. (2021). In their study of a traditional clay brick kiln, a transient CFD model was applied to examine the firing process with heat transfer represented through hydrodynamic equations and combustion reactions. While the kiln type differs from a tunnel kiln, the study is still important from a methodological point of view since it shows that brick firing quality is strongly influenced by time variations in internal combustion and heat transfer. Thus, the transient framework is relevant not only for modern kiln systems but also for understanding the general physics of brick firing.

The much of the earlier CFD research on tunnel kilns was based on steady or quasi-steady analyses at the zone level rather than on fully transient simulation of the firing process. The research from Abou-Ziyan (2004) investigated convective heat transfer for different brick arrangements in tunnel kilns and showed that brick stacking geometry has a strong effect on heat transfer performance. Subsequently, Mancuhan and Küçükada (2006) optimized fuel and air utilization in a tunnel kiln producing coal-admixed bricks, while Kaya et al. (2009) modeled the firing zone to identify optimal fuel feed locations and secondary air mass flow rates. These studies were highly valuable for kiln design and process optimization; however, they mainly addressed spatial flow and heat transfer behavior in selected kiln zones rather than the full-time dependent development of firing and emissions.

The studies also maintained this zone focused direction. The recent CFD analyses of the cooling zone in brick tunnel kilns investigated flow structures under different lattice configurations and showed that both turbulence modeling and channel geometry have a significant influence on air distribution and cooling effectiveness. The study by Refaey et al. reported that the BSL $k-\omega$ model agreed well with published experimental results for several lattice settings and showed that certain configurations produced stronger wall-channel flow and better cooling performance than others. The studies cited in the tunnel kiln energy literature have examined recovery airflow in the cooling zone, pressure drop, and flow uniformity, demonstrating that localized CFD analysis is valuable for process improvement. It is important to recognize that these works do not fully represent the transient thermal history of brick firing, which is particularly important in order to study heating from ambient temperatures to firing temperatures or to compare fuels and emission pathways dynamically.

This distinction is especially important for thesis research on tunnel brick kilns. A steady-state CFD model can provide about airflow patterns, burner mixing, temperature non uniformity, and local heat transfer behavior at a given operating condition. It cannot directly capture the way bricks are heated from an initial temperature to the required firing temperature, nor can it properly describe the time dependent evolution of exhaust gas composition. A transient model can represent the actual firing process, including ignition development, progressive heating, temporal temperature lag within the brick stack, and changes in outlet emissions over time. The transient studies suggest that this

approach is not only increasingly feasible but also more scientifically robust when the research focus involves heating duration, combustion staging, or dynamic emission formation.

The literature suggests that transient CFD studies of brick kilns remain limited especially in the case of tunnel brick kilns. In comparison with the large number of steady-state and simplified kiln analyses only a few studies have applied transient modeling and many of them are restricted to traditional kilns, individual kiln sections. A clear research gap still exists for studies that use transient CFD in tunnel brick kilns under realistic operating conditions, including temperature evolution, airflow behavior, fuel conversion, and emission characteristics. This type of research would be particularly useful to compare coal firing with alternative fuels such as natural gas, and to evaluate how air fuel ratio, residence time, and boundary conditions affect the overall performance of kilns.

The reviewed literature shows that CFD is now well-established approach for tunnel kiln analysis in the study of heat transfer, firing zone optimization, cooling zone flow behavior, and energy efficiency improvement. In the case of a thesis on tunnel brick kilns transient CFD provides a stronger and more defensible framework when the objective is to examine the progression of heating and combustion over time rather than a static snapshot of a single time interval.

2.14 Research gaps

The several studies on Nepal's brick industry provides important gaps that remain in understanding the performance of tunnel kiln technology under local operating conditions. The research focuses mainly on traditional kiln systems and there is limited integrated analysis combining energy performance, emission assessment, and financial feasibility. The quantitative linkage between kiln modernization and Nepal's climate commitments remains insufficient. To address these gaps is essential for supporting evidence based technological and policy decisions. The main research gaps can be listed as;

- Limited empirical data on energy performance of tunnel kilns in Nepal including SEC and thermal efficiency

- Insufficient plant level emission analysis for tunnel kilns including CO₂ estimation using fuel-based methods
- Inadequate financial analysis based on Nepal-specific production and market conditions
- Limited integration of energy, financial, and emission performance in a single analytical framework
- Transient CFD studies of tunnel brick kilns are still very limited

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Methodological framework

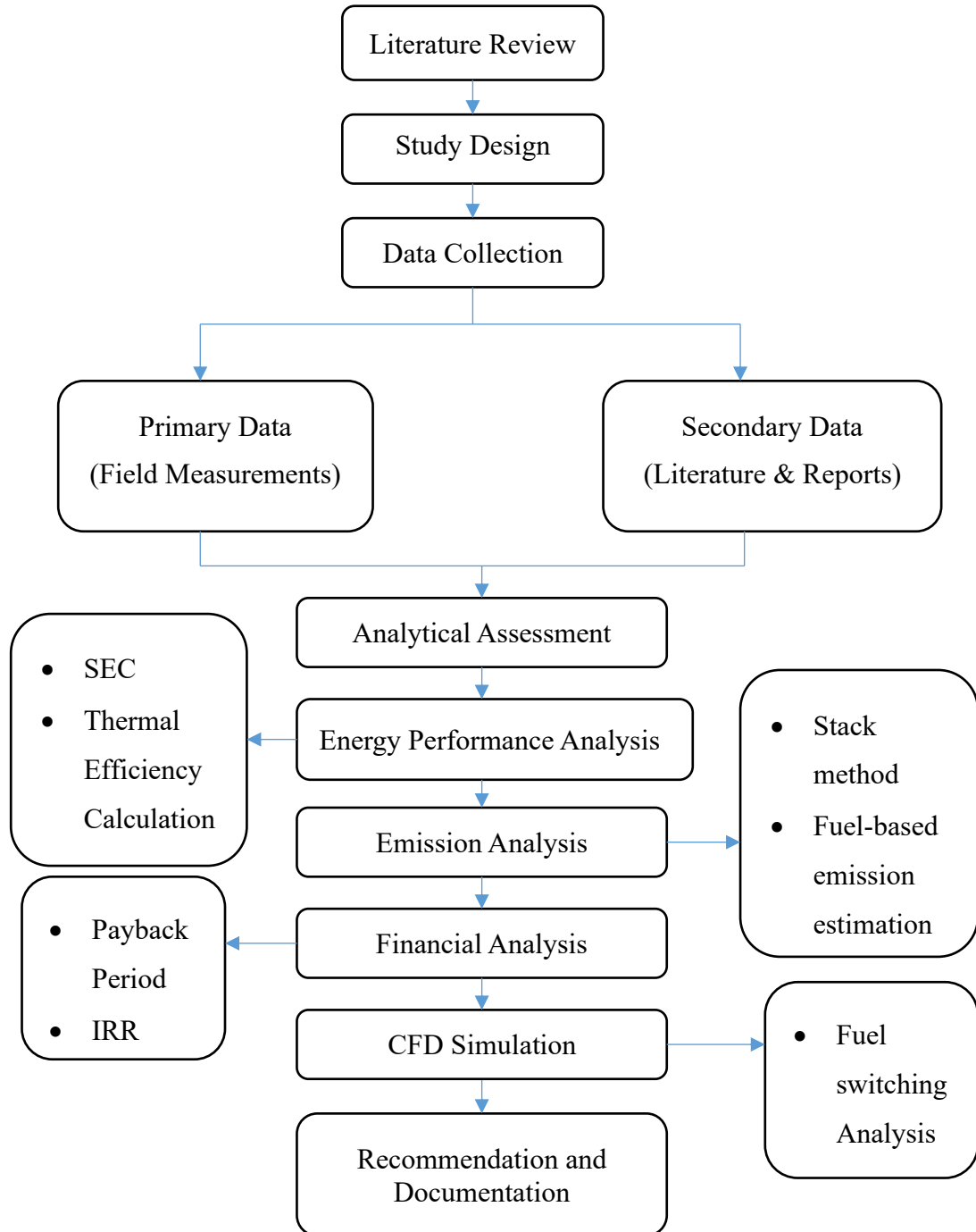


Figure 3.1: Methodological flow diagram

The methodological flow diagram of the study is shown in Figure 3.1. The study starts with a literature review and we design how to do the study. Then we collect data from both primary (field measurements) and secondary (reports and literature) sources. The data collected from the sources are analytical assessed comprising three primary components: energy performance analysis (SEC and thermal efficiency), emission analysis via stack and fuel-based estimation methods, and financial analysis through IRR and payback period. The results from these are analyzed and examined further in CFD simulation to assess fuel switching analysis. The findings from this analysis are synthesized to yield a comprehensive assessment and policy-relevant recommendations for the performance of tunnel brick kilns in Nepal.

3.2 Literature review

A thorough analysis of the literature on brick kiln technologies, energy performance benchmarks, emission estimation approaches, financial evaluation methods and transient CFD modeling is part of the study's initial phase. The Long-Term Strategy for Net-Zero emissions and Nepal's NDC 3.0 were among the policy documents that were examined. Finding important research gaps and appropriate analytical techniques are the goals of this review step.

3.3 Study design

A working tunnel brick kiln in Nepal was the subject of the case-based technical evaluation research. It made use of numerical simulations, analytical computations, and actual field data. Measuring SEC, thermal efficiency, CO₂ emissions, greenhouse gas emissions, and financial viability when the system was really operating on site was the focus of the field-based portion. Examining how combustion varies over time and how temperature is distributed in a typical tunnel kiln section under various combustion settings was the main focus of the simulation portion. The following performance metrics were established in accordance with the goals of the study:

- Specific energy consumption (SEC)
- Thermal efficiency (direct and indirect methods)
- CO₂ emission intensity (kg CO₂ per kg brick)
- IRR
- Payback period

3.4 Data collection

Two sources of data were gathered for this study: primary data from field measurements and secondary data from publications and literature that guarantee correctness and dependability. These were used in the energy performance, emission calculation, and financial viability analysis of the tunnel brick kiln.

3.4.1 Primary data collection

The field observations, production records, and meetings with technical staff were used to gather the primary data from the tunnel brick kiln in operation. The following list is among the primary data that was gathered:

- Daily coal consumption (kg/day)
- Total brick production (number/day)
- Average brick weight and dimensions
- Electricity consumption (kWh/day)
- Temperature measurements in preheating, firing, and cooling zones
- Moisture content of green bricks before firing
- Capital investment cost
- Operating and maintenance costs (fuel, labor, electricity, maintenance)

Coal consumption was recorded based on daily fuel input, and brick production information were verified by using kiln dispatch records. Operational records and mounted monitoring devices provided the temperature data. The instruments utilized to gather data are displayed in Table 3.1.

Table 3.1: Instruments used for data collection

S.N.	Parameter Measured	Instruments Used	Purpose / Formula (Where Applicable)
1	Coal Consumption	Digital Platform Weighing Scale	Measurement of daily coal input for energy and emission calculation

S.N.	Parameter Measured	Instruments Used	Purpose / Formula (Where Applicable)
2	Brick Weight	Digital Bench Scale	Determination of the Average Mass of Fired Bricks
3	Kiln Temperature (Preheating, Firing, Cooling Zones)	K-type Thermocouple with Data Logger	Monitoring temperature profile for thermal analysis
4	Electricity Consumption	Digital Energy Meter (kWh Meter)	Measurement of electrical energy input
5	Moisture Content of Green Bricks	Laboratory Oven (105°C) + Analytical Balance	$MC (\%) = (W_{wet} - W_{dry}) / W_{wet} \times 100$
6	Brick Production Rate	Kiln Car Loading Records & Dispatch Logs	Verification of daily production output for SEC calculation
7	Stack Gas Composition (CO ₂ , CO, O ₂ , NO _x , SO ₂ , Temperature)	E4500-N Portable Flue Gas Analyzer	Direct measurement of combustion gases and validation of emission estimation
8	Stack Gas Velocity	Hot-Wire Anemometer	Determination of volumetric flow rate
9	Mass Emission Rate	Calculated using Concentration + Flow Rate	$E = C \times Q \times \rho$ (for CO ₂ mass emission rate)

Where, W_{wet} = Initial weight of green brick, W_{dry} = Weight after oven drying at 105°C, C = Gas concentration (fraction), ρ = Gas density (kg/m³)

3.4.2 Secondary data collection

To support emission and energy calculations, secondary data was gathered from reliable literature, national reports, and international recommendations. These consist of the list below:

- Coal calorific value (MJ/kg) from literature and supplier specifications
- Emission factors (kg/TJ) from IPCC guidelines
- Carbon emission factor (CEF) and oxidation factor (OF)
- National SEC benchmarks for brick kilns
- Financial discount rates and economic parameters
- National and international greenhouse gas emission statistics and policy documents (NDC 3.0)

Secondary data were used to verify consistency with established methodologies and enabled comparison with national and regional benchmarks.

3.4.3 Data validation

The data was verified against production logs and pertinent industry standards to ensure accuracy and consistency. To lessen the effect of short-term changes in the kiln's operation values were averaged over typical operating days when necessary.

3.5 Energy performance analysis

This section shows the analytical formula that was used to figure out how well the tunnel brick kiln used energy. The calculations include both direct and indirect methods for finding the fuel energy input, useful heat, SEC, and thermal efficiency.

The fuel input in tunnel brick kiln is given as;

$$Q_{fuel} = \dot{m}_f \times CV \quad (3.1)$$

Where: Q_{fuel} = heat input from fuel (kcal/day), \dot{m}_f = fuel consumption (kg/day), CV = calorific value of fuel (kcal/kg).

The total mass of brick production is given as;

$$m_b = W_b \times N \quad (3.2)$$

Where: m_b = total mass of bricks (kg/day), W_b = weight per brick (kg), N = number of bricks per day.

The useful heat is given as;

$$Q_{\text{useful}} = m_b \cdot C_p \cdot (T_f - T_a) \quad (3.3)$$

Where: C_p = specific heat of brick (kcal/kg°C), T_f = firing temperature (°C), T_a = ambient temperature (°C).

The thermal efficiency of tunnel kiln by direct method is given as;

$$\eta_{\text{thermal}} = \left(\frac{Q_{\text{useful}}}{Q_{\text{fuel}}} \right) \times 100\% \quad (3.4)$$

Where: η_{thermal} = thermal efficiency of kiln (%)

The total energy input is given as;

$$\begin{aligned} E_{\text{total}} &= Q_{\text{fuel}} + E_{\text{ele}} \\ E_{\text{ele}} &= \text{kWh} \times 3.6 \end{aligned} \quad (3.5)$$

Where: E_{total} = total energy input (MJ/day), E_{ele} = electrical energy input (MJ/day), kWh = electricity consumption (kWh/day)

The SEC of brick kiln is given as below;

$$SEC = \frac{E_{\text{total}}}{N} \quad (3.6)$$

$$SEC_{\text{thermal}} = \frac{Q_{\text{fuel}}}{N} \quad (3.7)$$

Where: SEC = specific energy consumption per brick, SEC_{thermal} = thermal specific energy consumption per brick, N = Number of bricks per day

The indirect method, also known as the heat loss method, evaluates the thermal performance of the kiln by quantifying individual heat losses associated with combustion and heat transfer processes. The indirect method provides a more comprehensive thermodynamic assessment by considering the flue gas losses, moisture

related losses, surface heat losses, and losses due to incomplete combustion. The thermal efficiency by indirect method is determined by subtracting the sum of all calculated losses from 100 percent.

The indirect efficiency of tunnel brick kiln is calculated as;

The theoretical air requirement is given as;

$$A_{theoretical} = \frac{[11.6 \times C] + \left[34.8 \times \left(H_2 - \frac{O_2}{8}\right)\right] + [4.35 \times S]}{100} \text{ kg/kg of coal} \quad (3.8)$$

The % Excess air needed to be supplied is;

$$EA = \frac{O_2\%}{21 - O_2\%} \times 100 \quad (3.9)$$

The actual mass of air supplied is;

$$\begin{aligned} \text{Actual mass of air supplied /kg of fuel (AAS)} \\ = \left[1 + \frac{EA}{100}\right] \times A_{theoretical} \end{aligned} \quad (3.10)$$

The heat loss due Dry flue gas in percentage (L_1) is given as;

$$L_1 = \frac{m \times C_p \times (T_f - T_a)}{GCV \text{ of fuel}} \times 100 \quad (3.11)$$

Where: m is total mass of flue gas = mass of actual air supplied plus mass of fuel supplied, C_p is Sp. Heat of flue gas, T_f = Flue gas temperature, T_a = Ambient Temperature

The heat Loss due to hydrogen in fuel in percentage (L_2) is given as;

$$L_2 = \frac{9 \times H_2 \times [584 + C_p \times (T_f - T_a)]}{GCV \text{ of fuel}} \times 100 \quad (3.12)$$

Where: H_2 = hydrogen content in fuel (kg/kg fuel), 584 = latent heat

The heat loss due to moisture present in fuel in percentage (L_3) is;

$$L_3 = \frac{\% \text{ Moisture} \times [584 + C_p \times (T_f - T_a)]}{GCV \text{ of fuel}} \times 100 \quad (3.13)$$

Where: % Moisture = moisture content in fuel (%)

The heat loss due to moisture present in air in percentage (L_4) is given as;

$$L_4 = \frac{AAS \times \text{humidity} \times C_p \times (T_f - T_a)}{GCV \text{ of fuel}} \times 100 \quad (3.14)$$

Where: humidity = moisture content of air (kg/kg dry air)

The sensible heat loss due to unloaded bricks in percentage (L_5) is given as;

$$L_5 = \frac{m_b \cdot C_p (T_{unload} - T_a)}{Q_{fuel}} \times 100 \quad (3.15)$$

Where: T_{unload} = Unloading temperature of fired bricks

The heat loss due to moisture present in green bricks in percentage (L_6) is;

$$L_6 = \frac{m_w (c_{pw} (100 - T_a) + 584)}{Q_{fuel}} \times 100 \quad (3.16)$$

Where: m_w = mass of moisture in green bricks, c_{pw} = specific heat of water

Now, the Surface loss is given as;

$$Q_{surface} = A [h_c (T_s - T_a) + \varepsilon \sigma (T_s^4 - T_a^4)] \quad (3.17)$$

$$Q_{\text{total surface losses}} = Q_{\text{pre-heating}} + Q_{\text{firing}} + Q_{\text{cooling}} + Q_{\text{drying}} \quad (3.18)$$

Where: A = surface area (m^2), h_c = convective heat transfer coefficient, T_s = surface temperature, ε = emissivity, σ = Stefan–Boltzmann constant

The Surface loss in percentage (L_7) is given as;

$$L_7 = \frac{\text{total surface losses} \cdot 24 \cdot 60 \cdot 60}{Q_{fuel} \cdot 1000} \times 100 \quad (3.19)$$

The heat loss due to incomplete combustion in percentage (L_8) is given as;

$$L_8 = \frac{CO}{CO_2 + CO} \times 5630 \quad (3.20)$$

Where: CO, CO_2 = measured flue gas components

The minor and unaccounted losses such as opening losses during kiln car movement, door leakages, and short-term operational disturbances were assumed negligible and were not separately evaluated in the heat balance. Their contribution is relatively small compared to dominant thermal losses and does not significantly influence overall efficiency estimation.

Now, the indirect thermal efficiency of tunnel kiln is given as;

$$\begin{aligned} \eta_{\text{indirect}} &= 100 - (\text{Sum of all the heat losses}\%) \\ &= 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8) \end{aligned} \quad (3.21)$$

3.6 Financial analysis

We used discounted cash flow methods to figure out if the tunnel brick kiln would be a good investment. To determine the IRR and payback period for various production capacity levels, the research took into account the capital expenditure, operating costs, annual revenue, and net cash flow.

The present value of cash flow is given as;

$$PV_t = \frac{CF_t}{(1+r)^t} \quad (3.22)$$

Where: PV_t = present value of cash flow in year t , CF_t = cash flow in year t , r = discount rate, t = year

The Cumulative discounted cash flow is given as;

$$\text{Cumulative } PV_t = \sum_{t=1}^n \frac{CF_t}{(1+r)^t} \quad (3.23)$$

The discounted payback period is the time required for the cumulative present value of cash flows to equal the initial investment. The shorter the DPP, the quicker the initial investment is recovered. Shorter discounted payback periods are preferred for projects as they reduce financial risk and improve liquidity. The general discounted payback formula is given as;

$$DPP = \text{Last year with negative cumulative PV} + \frac{\text{Remaining unrecovered amount}}{\text{Discounted cash flow in next year}} \quad (3.24)$$

$$DPP = \min\{t \mid \sum_{i=1}^t \frac{CF_i}{(1+r)^i} \geq C_0\}$$

The practical Calculation of DPP is given as;

$$DPP = t + \frac{C_0 - \sum_{i=1}^t \frac{CF_i}{(1+r)^i}}{\frac{CF_{t+1}}{(1+r)^{t+1}}} \quad (3.25)$$

Where: C_0 = initial investment, CF_i = annual net cash flow, r = discount rate, t = last year before full recovery

The decision Criterion for the project like tunnel brick kiln are

- Accept the project if: $DPP \leq$ Maximum acceptable payback period
- Reject the project if: $DPP >$ Maximum acceptable payback period

The capital-intensive projects such as tunnel brick kilns, a shorter DPP supports investment viability.

Also, The IRR is the discount rate at which the Net Present Value (NPV) becomes zero. If IRR exceeds the required rate of return, the project generates returns higher than the minimum acceptable level and is financially viable. If IRR is lower than the required rate, the project does not meet investment expectations.

The IRR is calculated as;

$$NPV = \sum_{t=1}^n \frac{CF_t}{(1+r)^t} - C_0 \quad (3.26)$$

IRR is the value of r such that: $NPV = 0$

Where: r = discount rate, n = project life (years), CF_t = cash flow in year t

The Decision Criterion for IRR is;

- Accept the project if: $IRR > r_{\text{required}}$
- Reject the project if: $IRR < r_{\text{required}}$

Where, r_{required} = required rate of return (or cost of capital)

For a tunnel brick kiln: An investment is considered economically viable if its IRR exceeds the prevailing bank interest rate or the industry benchmark rate of return.

3.7 Emission analysis

The emission performance of the tunnel brick kiln was evaluated using both stack gas measurements and fuel-based emission estimation. Stack-based approaches provide information about combustion gases during operation, whereas fuel-based approaches estimate CO₂ emissions based on coal consumption. By combining these two methods, the overall emission assessment gets more robust and reliable.

3.7.1 Stack gas measurement method

Stack emissions were measured using the E4500-N portable flue gas analyzer under steady-state kiln operating conditions.

Parameters Measured:

- CO₂ (% volume)
- CO (ppm)
- NO_x (ppm)
- CH₄(ppm)
- SO₂(ppm)
- O₂ (% volume)
- Flue gas temperature (°C)
- Excess air (%)

Stack velocity was measured separately to determine volumetric flow rate.

The Volumetric Flow Rate is given as;

$$Q = V \times A \quad (3.27)$$

Where: Q = volumetric flow rate (m^3/s), V = stack gas velocity (m/s), A = stack cross-sectional area (m^2)

The mass flow rate of Flue gas is given as;

$$m_{fg} = \rho \times Q \quad (3.28)$$

Where: ρ = flue gas density (kg/m^3)

The CO_2 Mass Emission Rate is calculated as;

$$E_{CO_2} = C_{CO_2} \times Q \times \rho \quad (3.29)$$

Where: C_{CO_2} = CO_2 concentration (fraction)

The CO Emission Rate (ppm-based) is calculated as;

$$E_{CO} = \frac{C_{ppm} \times MW \times Q}{24.45} \quad (3.30)$$

Where: MW = molecular weight of gas, 24.45 = molar volume at standard condition (L/mol)

3.7.2 Fuel-based emission estimation

The CO_2 emissions were also estimated based on fuel consumption using carbon balance principle as;

$$CO_2 = FC \times Cf \times OF \times \frac{44}{12} \quad (3.31)$$

Where: FC = fuel consumption (kg/day), Cf = carbon mass fraction, OF = oxidation factor, $44/12$ = molecular weight ratio (CO_2/C)

The Emission intensity is given as;

$$\text{Emission intensity} = \frac{CO_2}{m_{brick}} \quad (3.32)$$

Where: m_{brick} = total brick mass produced, Emission intensity is expressed in kg CO_2 per kg of fired brick. Oxygen and CO levels were used to evaluate combustion performance.

3.7.3 GHG emissions from brick kilns

The greenhouse gas (GHG) emissions from brick production were quantified following the IPCC Guidelines for National Greenhouse Gas Inventories (2006, 2019 Refinement) and Global Warming Potential (GWP100) values from IPCC AR6 (2021).

The general summation form of CO₂-equivalent (CO₂e) for multiple greenhouse gases is given as;

$$CO_2e = \sum_{i=1}^n (E_i \times GWP_i) \quad (3.33)$$

Where: CO_2e = CO₂-equivalent, E_i = Emission of gas i (tons), GWP_i = Global Warming Potential of gas i (IPCC AR6, 100-year horizon)

3.8 Geometric model of tunnel brick kiln section

This CAD model as shown in Figure 3.2 represents a quarter section of one tunnel kiln cart, containing 25% of the total 5,040 bricks. In order to reflect the actual loading

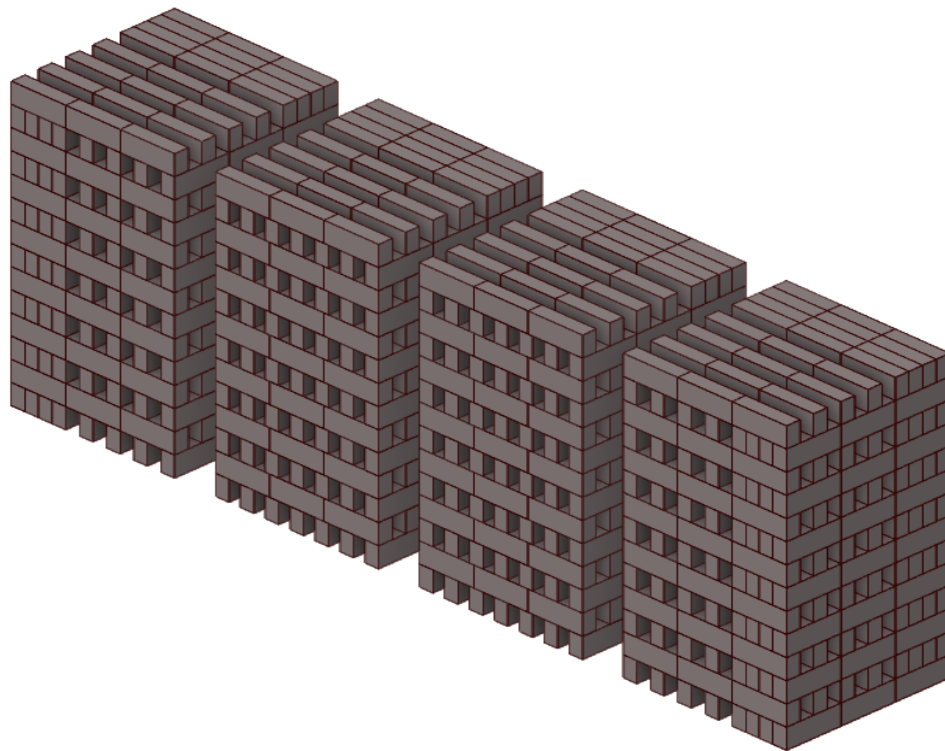


Figure 3.2: Geometric model of tunnel brick kiln section

configuration inside the kiln, the bricks are stacked in an orderly pattern. Because it preserves the representative brick arrangement and reduces computational complexity, this reduced model is useful for visualization and numerical analysis. Under tunnel kiln conditions, it allows for the study of heat transfer, airflow distribution, and temperature variation within the brick stack.

3.9 Mesh Generation

The computational domain was generated as a hybrid mesh (approximately 4.2 million elements). Prismatic layers were used in the computational domain near the walls and a poly-hexcore mesh in the core region. The mesh quality parameters had the minimum orthogonal quality of 0.63 and the maximum skew of 0.52, which indicated that the mesh quality was good and was suitable to the stable and reliable numerical simulation of heat transfer and fluid flow inside the tunnel brick kiln as shown as in Figure 3.3.

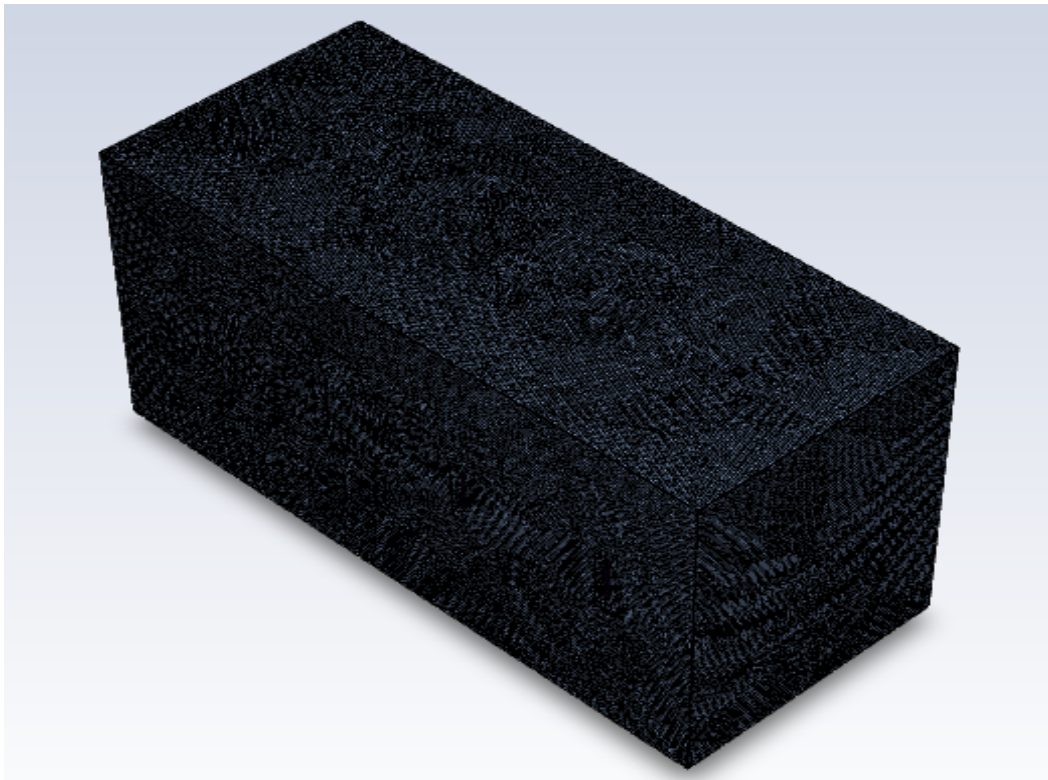


Figure 3.3: Mesh generation

The CFD model was developed to simulate transient coal combustion inside the tunnel kiln. The computational domain was discretized using an unstructured mesh to properly capture the complex kiln geometry and brick arrangement. Conjugate heat transfer analysis was used to account for heat exchange between the gas phase, solid bricks, and

surrounding kiln structure. Turbulence was modeled using the standard $k-\epsilon$ model, while radiative heat transfer was included using the Discrete Ordinates (DO) radiation model. The pressure–velocity coupling was solved using the SIMPLE algorithm, and the governing equations were discretized using a second-order upwind scheme to improve numerical accuracy.

A transient non-premixed combustion model was applied because coal combustion involves time-dependent fuel–air mixing and reaction processes. The simulation was carried out under adiabatic and continuous firing assumptions to represent the operating condition of the tunnel kiln. In addition, a mesh independence test was performed before the final simulations to ensure that the predicted temperature was not significantly affected by mesh size. Based on this test, the selected mesh was used for all combustion cases to maintain accuracy and fair comparison among different operating conditions.

3.10 Mesh independence test

A mesh independence test was conducted for the coal combustion case at a stoichiometric ratio of 1.0 to evaluate the influence of mesh refinement on the predicted temperature. Five different mesh sizes were tested, ranging from 2.67 million to 6.40 million elements. As shown in the Table 3.2, the predicted temperature increased from 918.11 °C for the 2.67 million element mesh to 930.20 °C for the 6.40 million element mesh. However, the increase in temperature became progressively smaller as the mesh was refined. The temperature difference decreased from 6.66 °C between Mesh 1 and Mesh 2 to only 0.80 °C between Mesh 4 and Mesh 5, indicating that the numerical solution was approaching mesh-independent behavior.

Table 3.2: Mesh independence test

Mesh no.	Number of elements (million)	Predicted temperature (°C)	Difference from previous mesh (°C)	Percentage change (%)
1	2.67	918.11	—	—
2	3.50	924.77	6.66	0.73
3	4.20	928.14	3.37	0.36
4	5.40	929.40	1.26	0.14
5	6.40	930.20	0.80	0.09

The 4.20 million element mesh was selected for the final simulation because the variation in predicted temperature beyond this mesh was very small. The temperature

difference between the 4.20 million and 5.40 million element meshes was only 1.26 °C, corresponding to a percentage change of 0.14%. Further refinement to 6.40 million elements changed the temperature by only 2.06 °C compared with the selected mesh, which is also very small for a combustion simulation. Therefore, the 4.20 million element mesh was considered sufficiently accurate while avoiding the additional computational time and cost required for finer meshes.

The Figure 3.4 shows the variation of predicted temperature with increasing mesh size for the coal combustion case at a stoichiometric ratio of 1.0. The temperature rises sharply from 918.11 °C at 2.67 million elements to 928.14 °C at 4.20 million elements, showing that the coarser meshes were still influencing the numerical result. However, after 4.20 million elements, the curve becomes almost flat, indicating that further mesh refinement has only a minor effect on the predicted temperature.

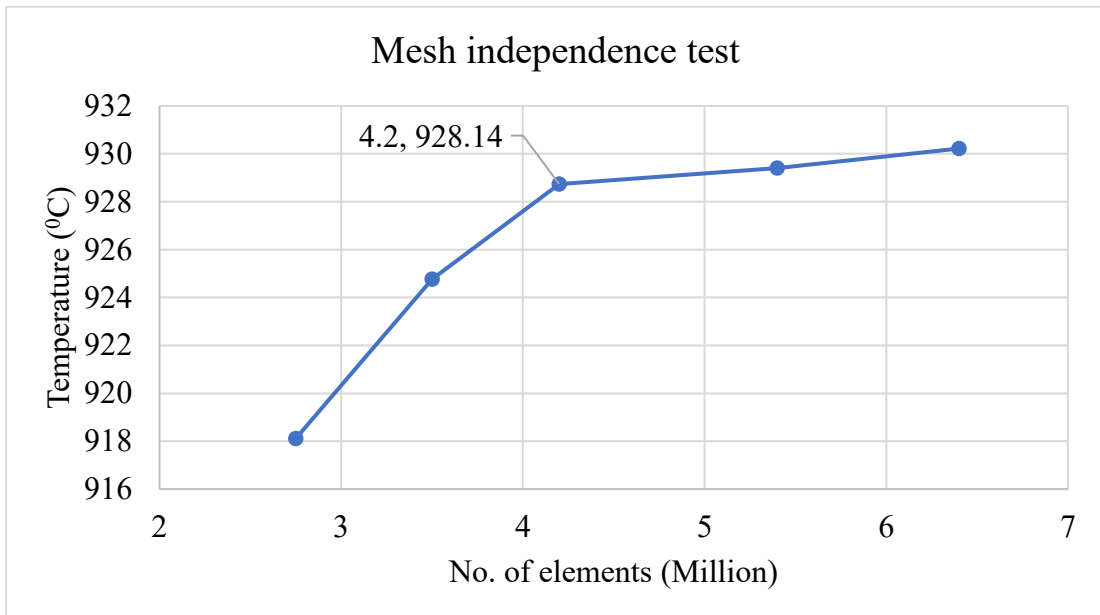


Figure 3.4: Mesh independence test for coal combustion at stoichiometric ratio 1.0

The selected mesh size of 4.20 million elements is marked in the figure because it represents the point where the solution starts approaching mesh-independent behavior. Beyond this point, the temperature increases only slightly, reaching 929.40 °C at 5.40 million elements and 930.20 °C at 6.40 million elements. This small change confirms that the 4.20 million element mesh provides sufficient accuracy while avoiding unnecessary computational cost. Therefore, this mesh was used for all subsequent

combustion simulations to maintain consistency and fair comparison among different cases.

3.11 Transient combustion model

The transient combustion (TC) model requires to solve the fluid flow through the equations of Continuity, Navier–Stokes, and Standard k-ε Turbulence model, as shown in the Equations;

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (3.34)$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + (\rho \mathbf{u} \cdot \nabla) = \rho \mathbf{g} - \nabla P + \nabla \cdot [\mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) + \tau(t)] \quad (3.35)$$

Where: ρ denotes fluid density, t represents time, and $\tau(t)$ indicates the Reynolds stress tensor. This term can be further written, as shown in Equation (3.36), using the mean velocity fluctuations (u'), turbulent kinetic energy (k), identity tensor (I), and turbulent eddy viscosity (μ_t).

$$\tau(t) = \rho u' u' - \frac{2}{3} \rho k I = \mu_t (\nabla u + (\nabla u)^T) \quad (3.36)$$

The k-ε turbulence model is based on two transport equations that represent the turbulent kinetic energy (k) and its rate of dissipation (ε).

$$\frac{\partial(\rho k)}{\partial t} + (\rho u \cdot \nabla) k = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho \quad (3.37)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + (\rho u \cdot \nabla) \varepsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} P_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (3.38)$$

Where: P_k denotes the generation of turbulent kinetic energy caused by velocity gradients, as given in Equation (3.39). The turbulent viscosity is then defined in Equation (3.40) as a function of the governing turbulence variables.

$$P_k = -\rho\mu_t \left[2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right] \quad (3.39)$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3.40)$$

Where: C_μ , $C1\varepsilon$, and $C2\varepsilon$ are empirical constants of the turbulence model, and σ_k and σ_ε denote the turbulent Prandtl numbers associated with k and ε , respectively. The standard values are $C_\mu = 0.09$, $C1\varepsilon = 1.44$, $C2\varepsilon = 1.92$, $\sigma_k = 1$, and $\sigma_\varepsilon = 1.3$. In addition, Equation (3.41) governs temperature prediction by accounting for convective heat transfer from hot gases flowing through the zigzag channels and conductive heat transfer within the bricks as;

$$\frac{D(\rho c T)}{Dt} = \lambda \nabla^2 T \quad (3.41)$$

Moreover, pollutant-species formation is predicted using the mixture fraction approach, in which chemical equilibrium is represented through one or two conserved mixture fractions, allowing complex chemical reactions to be simplified. Under this approach, all thermo-chemical scalar quantities are expressed as functions of the mixture fraction (f), as presented in Equations (3.42) and (3.43)). This method is commonly applied in turbulent flows where turbulent convection dominates over molecular diffusion.

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \quad (3.42)$$

$$\frac{\partial(\rho f)}{\partial t} + \nabla \cdot (\rho u f) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla f \right) \quad (3.43)$$

In addition, Equation (3.44) has to be solved for the mixture fraction variance. The mixture fraction variance is employed in the closure model to describe turbulence chemistry interactions. The equations for individual species are not solved. Instead, species concentrations are derived from the predicted mixture fraction fields. The thermochemistry calculations were performed in a preprocessing step and then tabulated for look-up in ANSYS FLUENT. The interaction between chemistry and turbulence was considered via an assumed-shape Probability Density Function (PDF).

$$\frac{\partial(\rho f'^2)}{\partial t} + \nabla \cdot (\rho u f'^2) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla f'^2 \right) + C_g \mu_t (\nabla f)^2 - C_d \rho \frac{\varepsilon}{k} f'^2 \quad (3.44)$$

Where: $f' = f - \bar{f}$, representing the fluctuation of the mixture fraction from its mean value. The default values of the constants are $\sigma_t = 0.85$, $C_g = 2.86$, and $C_d = 2.0$, respectively.

The DO radiation model solves the radiative transfer equation by dividing the angular space into a finite number of discrete directions and accounting for radiation absorption, emission, and scattering within the medium. For many kiln combustion cases, scattering is negligible, so the equation becomes;

$$\nabla \cdot (I(\vec{r}, \vec{s}) \vec{s}) + aI(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} \quad (3.45)$$

Where $I(\vec{r}, \vec{s})$ denotes radiation intensity, \vec{r} represents position vector, \vec{s} is the direction vector, a is the absorption coefficient, n is refractive index, σ is the Stefan–Boltzmann constant, and T denotes absolute temperature.

The CFD simulation of the brick-firing process inside the kiln was carried out. A transient solution approach was adopted to capture the time-dependent thermal behavior inside the kiln. The governing flow equations, together with pressure–velocity coupling, were solved using the SIMPLE algorithm.

3.12 Boundary conditions and setup

The boundary conditions were defined using the equivalence ratio (ϕ). The equivalence ratio shows whether the fuel–air mixture has less, exact, or excess fuel compared with the stoichiometric requirement. A value of (ϕ) = 1.0 represents stoichiometric combustion, where fuel and air are supplied in the ideal theoretical ratio. A lean combustion case was considered at (ϕ)= 0.7 where excess air is present and the mixture contains less fuel. A rich combustion case was considered at (ϕ)= 1.4 where excess fuel is present and the air supply is insufficient. These three cases were used to compare how fuel–air conditions affect temperature distribution and combustion performance. Thus, lean, stoichiometric, and rich conditions were simulated to evaluate the kiln behavior under different operating scenarios. For each condition, two different fuels

coal and natural gas were analyzed to compare their combustion behavior as shown in Table 3.3.

Table 3.3: Inlet boundary conditions for the CFD analysis

Equivalence ratio (ϕ)	Fuel	Mass flow rate of fuel (kg/s)	Mass flow rate of air (kg/s)
1	Coal	0.03960	0.396
	Natural gas	0.01782	0.307
0.7	Coal	0.03960	0.277
	Natural gas	0.01782	0.215
1.4	Coal	0.03960	0.554
	Natural gas	0.01782	0.429

The mass flow rate of the fuel was maintained constant with each respective fuel in all the equivalence ratios with coal fed at a rate of 0.03960 kg/s and natural gas fed at a rate of 0.01782 kg/s. Mass flow rate of air was adjusted to bring about the desired equivalence ratios. At stoichiometric conditions ($\phi = 1.0$), the air mass flow rates were adjusted to 0.396 kg/s when using coal and 0.307 kg/s when using natural gas, which ensures full combustion of the fuel and no excess air or fuel.

For lean combustion ($\phi = 0.7$), air supply was reduced relative to the stoichiometric reference, resulting in air mass flow rates of 0.277 kg/s for coal and 0.215 kg/s for natural gas. For rich combustion ($\phi = 1.4$), air flow was increased to 0.554 kg/s for coal and 0.429 kg/s for natural gas because the fuel-to-air ratio was higher.

The temperature throughout the entire computational domain, both the air and kiln bricks, had a uniform initial temperature of 288.35 K. The transient simulation was done using a time step of 900 s. The thermal physiological properties of the bricks were assumed to be constant during the firing process, which was 15 hours long, and the thermal conductivity of the bricks was 0.66 W/m³K, density of 1510 kg/m³, and specific heat capacity of 790 J/kg K.

3.13 Stoichiometric Combustion Reactions and Excess Air

The stoichiometric combustion reactions for coal and natural gas were used to determine the theoretical air requirement and species generation during CFD combustion analysis.

Fuel	Stoichiometric Reactions
Coal	$C_1H_{0.8}O_{0.1}N_{0.02}S_{0.01} + 1.16(O_2 + 3.76N_2) \rightarrow CO_2 + 0.4H_2O + 0.01SO_2 + 4.3716N_2$
Natural Gas	$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$

The air–fuel (AF) ratio is applied in the combustion process to represent the proportion of air supplied relative to the amount of fuel used is given as;

$$AF = \frac{\dot{m}_A}{\dot{m}_F} = \frac{N \cdot M_A}{N_C \cdot M_C + N_H \cdot M_H} \quad (3.46)$$

Where: \dot{m}_A refers to the air mass flow rate, \dot{m}_F indicates the fuel mass flow rate, N represents the number of moles, and M denotes the molar mass.

The percentages of excess air and deficient air are determined from the actual and stoichiometric air–fuel ratios, as presented in Equations (3.47) and (3.48).

$$\% \text{Excess of Air} = \left(\frac{AF_{\text{actual}}}{AF_{\text{stoichiometric}}} - 1 \right) \cdot 100 \quad (3.47)$$

$$\% \text{Deficiency of Air} = \left(1 - \frac{AF_{\text{actual}}}{AF_{\text{stoichiometric}}} \right) \cdot 100 \quad (3.48)$$

The equivalence ratio (ϕ) is defined as the ratio of the actual fuel–air ratio to the stoichiometric fuel–air ratio, or equivalently the inverse ratio of actual to stoichiometric air–fuel ratio and is given as;

$$\phi = \frac{(F/A)_{\text{actual}}}{(F/A)_{\text{stoichiometric}}} = \frac{(A/F)_{\text{stoichiometric}}}{(A/F)_{\text{actual}}} \quad (3.49)$$

Where: $\phi = 1$ means exact stoichiometric combustion, $\phi < 1$ means excess air (lean combustion), and $\phi > 1$ means insufficient air (fuel-rich combustion).

3.14 Energy, Emission and Cost Reduction

The useful energy required for tunnel kiln is given as;

$$E_{required} = m_b \cdot C_p \cdot (T_f - T_a) \quad (3.50)$$

Where: m_b = total mass of bricks (kg/day), C_p = specific heat of brick (kcal/kg°C), T_f = firing temperature (°C), T_a = ambient temperature (°C)

The fuel energy input required is obtained from the ratio of useful energy demand to the thermal efficiency of the system and is given as;

$$FE_{required} = \frac{E_{required}}{\text{thermal efficiency of fuel kiln}} \quad (3.51)$$

The energy reduction is given as;

$$E_{reduction} = E_{coal} - E_{natural\ gas} \quad (3.52)$$

Where: E_{coal} = energy required for coal kiln $E_{natural\ gas}$ = energy required for natural gas kiln

The mass of fuel required is given as;

$$m_{fuel} = \frac{E_{fuel}}{GCV_{fuel}} \quad (3.53)$$

Where: m_{fuel} = mass of fuel required, E_{fuel} = fuel energy required, GCV_{fuel} = gross calorific value of fuel

The CO₂ emissions based on fuel consumption is given as;

$$CO_2 = FC \times Cf \times OF \times \frac{44}{12} \quad (3.54)$$

Where: FC = fuel consumption (kg/day), Cf = carbon mass fraction, OF = oxidation factor, $44/12$ = molecular weight ratio (CO₂/C)

The emission reduction is given as;

$$Em_{\text{reduction}} = Em_{\text{coal kiln}} - Em_{\text{natural gas kiln}} \quad (3.56)$$

Where: $Em_{\text{coal kiln}}$ = emission from coal kiln, $Em_{\text{natural gas kiln}}$ = emission from natural gas kiln

The total annual cost for fuel is given as;

$$\text{Annual cost of fuel} = P_{\text{fuel}} * m_{\text{fuel}} \quad (3.57)$$

Where: P_{fuel} = price of fuel (NPR/kg)

The cost reduction is given as;

$$C_{\text{reduction}} = C_{\text{coal}} - C_{\text{natural gas}} \quad (3.58)$$

Where: C_{coal} = total annual cost of coal, $C_{\text{natural gas}}$ = total annual cost for natural gas

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter discusses the results of the energy performance assessment, emission analysis and financial evaluation of the tunnel brick kiln and reflects on them. The results are studied to understand the operational efficiency of the kiln, the major sources of energy loss, the level of emissions and the overall economic feasibility of the benefits of fuel switching. The technical, environmental and economic factors are discussed in order to provide a thorough evaluation of tunnel kiln performance.

4.1 Fuel consumption in green bricks

The fuel used is combination of three types: - one is Raniganj coal with GCV of 5,000kcal/kg, other is US Coal with 7,500Kcal/kg and the last one is Sawdust with 3,000kcal/kg. The Raniganj coal is used as internal fuel and is mixed with the soil in the ratio of 1:10 (Coal: Soil) by volume. The US Coal and Saw dust are mixed in the ratio of 1:2 (US Coal: Sawdust) by volume. The combined GCV is calculated as follow;

Total Raniganj coal used per day = 11,490 kg/day; US coal + sawdust mixture = 400 kg/day; Total fuel consumption = 11,490+400=11,890 kg/day

$$W_1 = 11,490/11,890 = 0.966; W_2 = 400/11,890 = 0.033$$

Where, W_1 = weight fraction of Raniganj coal, W_2 = weight fraction of US coal + sawdust

The GCV of US Coal + Sawdust Mixture combined is;

$$\begin{aligned} GCV_{(US+Sawdust)} &= 0.75 \times 7,500 + 0.25 \times 3,000 \\ &= 6,375 \text{ kcal/kg} \end{aligned}$$

The Total Combined GCV of Fuel is;

$$\begin{aligned} GCV_{total} &= GCV_R \times W_1 + GCV_{(US+SD)} \times W_2 \\ &= (5,000 \times 0.966) + (6,375 \times 0.033) \\ &= 4,830+210.4 \\ &= 5,040.4 \text{ kcal/kg} \end{aligned}$$

4.2 Measured primary parameters

The primary parameters were measured directly at the tunnel brick kiln during steady-state operating conditions. These comprised the calorific value of the fuel mixture, the daily fuel consumption (kg/day), and the brick output rate (number of bricks/day). A portable flue gas analyzer was used to measure stack gas properties such CO₂ (%), CO (ppm), O₂ (%), and flue gas temperature (°C). The volumetric flow rate was calculated by measuring the stack gas velocity (m/s) independently. An infrared (IR) thermometer was used to measure the surface temperatures of kiln zones in order to calculate surface heat losses. The oven drying method was used to determine the moisture content of green bricks. The CFD simulation, energy performance evaluation, emission computation, and financial assessment were all based on these observable features. The parameters of tunnel kin are shown in Table 4.1.

Table 4.1: Parameters of tunnel kiln

S. N	Description	Value
1	Brick Production (Number/day)	60,480
2	Average wt. of One Fired brick(kg)	2.5
3	Total fuel consumption (Raniganj+ US Coal+ Sawdust) (kg/day)	11,890
4	Total Combined GCV of Fuel (kcal/kg)	5,040.4
5	Specific heat of brick (kcal/kg°C),	0.20
6	Firing Temperature (°C)	930
7	Ambient Temperature (°C)	15.2
8	Average O ₂ percentage in flue gas (%)	17
9	Exit flue gas temperature (°C)	52

4.3 Energy performance evaluation

In this study both direct and indirect methods were used to evaluate the energy performance of the tunnel brick kiln. The study was carried out to determine the SEC, total fuel energy input, useful heat absorbed by the bricks and overall thermal efficiency of the kiln. The comparison of direct and indirect efficiencies was the check on the validity of the heat balance calculations. The energy performance assessment provided an insight into operational efficiency, effectiveness of fuel use and potential areas for energy saving opportunities in the tunnel brick kiln. The efficiency of the furnace using direct method was calculated as given in Table 4.2.

Table 4.2: Efficiency of tunnel kiln using direct method

S. N	Parameters	Value
1	Fuel used	Coal + Saw dust
2	Fuel input (kcal/day)	59,930,356
3	Total mass of bricks (kg/day)	151,200
4	Useful Heat (kcal/day)	27,663,552
5	Thermal Efficiency (%)	46.15%

The thermal efficiency of tunnel brick kiln was found to be 46.15% by direct method. This value falls within the typical efficiency range of 45–65% reported for tunnel brick kilns in previous studies (Hasanbeigi et al., 2013; Madloul et al., 2011). Therefore, the evaluated kiln operates within the acceptable range. However, the obtained value is closer to the lower bound of this range, which may be associated to heat losses through kiln walls and dry flue gas losses due to excess combustion air.

The SEC of tunnel kiln was calculated as shown in Table 4.3.

Table 4.3: SEC of tunnel Kiln

S. N	Description	Value
1	Monthly Average Electricity Consumption (KWh/month)	78529
2	Total Electrical Energy Consumption (MJ/day)	9424
3	Fuel input (MJ/day)	251707.5
4	Total Energy input (Fuel + Electrical) (MJ/day)	261131.5
5	SEC (MJ/kg of fired bricks)	1.72
6	SEC (MJ/1000 bricks)	4310
7	Thermal SEC (MJ/kg of fired bricks)	1.66
8	Thermal SEC (MJ/1000 bricks)	4160
9	Electrical SEC (MJ/kg of fired bricks)	0.06
10	Electrical SEC (1000 bricks)	155.82

The SEC of the tunnel kiln was found to be 1.72 MJ/kg of fired bricks, with 1.66 MJ/kg from thermal energy and 0.06 MJ/kg from electrical energy, as shown in Table 4.3. Therefore, the contribution of electrical energy is negligible and most of the energy required for brick firing is obtained from combustion of fuel. The calculated SEC is within the common range of 1.3–1.8 MJ/kg for tunnel brick kilns which indicates that the kiln is functioning within the acceptable range of energy performance (Hasanbeigi et al., 2013; Zhang et al., 2016). This means that the kiln is efficient but there is still room for improvement especially in controlling the combustion and reducing the excess air.

The efficiency of tunnel kiln using indirect method was calculated as shown in Table 4.4.

Table 4.4: Efficiency of tunnel kiln using indirect method

S. N	Description	Value
1	Dry Flue Gas Loss	
	Theoretical air requirement to burn 1 kg of Fuel (kg)	7.7
	Excess air (%)	425
	Actual mass of air supplied (kg/kg of fuel)	40.42
	Total mass of flue gas (kg/kg of fuel)	41.42
	Heat loss in flue gas (%)	7
2	Heat loss due to evaporation of water formed due to H ₂ in fuel	
	Hydrogen (%)	5
	Heat loss (%)	5.36
3	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	3
	Heat loss (%)	0.35
4	Heat loss due to moisture present in air	
	Relative Humidity at 15.2 (%)	55
	Heat loss (%)	0.09
5	Sensible heat loss in Unloaded bricks	
	Temperature of Unloaded bricks (°C)	50
	Heat loss (%)	2
6	Heat loss due to moisture present in green bricks	
	mass of green bricks (kg)	3.06
	Moisture present in green brick (%)	10
	Heat loss (%)	18.33
7	Heat loss through surfaces	
a	Preheating Zone	
	Average surface temperature of top section (°C)	32
	Average surface temperature of right section (°C)	27.3
	Average surface temperature of left section (°C)	29
	Surface area of top section (m ²)	372.24
	Surface area of right section (m ²)	89.1
	Surface area of left section (m ²)	89.1
	Total heat loss through preheating zone (kw)	120.91
b	Firing Zone	
	Average surface temperature of top section (°C)	43.5
	Average surface temperature of right section (°C)	28.5
	Average surface temperature of left section (°C)	31

S. N	Description	Value
	Surface area of top section (m ²)	345.92
	Surface area of right section (m ²)	82.8
	Surface area of left section (m ²)	82.8
	Total heat loss through firing zone (kw)	175.08
c	Cooling Zone	
	Average surface temperature of top section (°C)	26
	Average surface temperature of right section (°C)	23.3
	Average surface temperature of left section (°C)	22
	Surface area of top section (m ²)	372.24
	Surface area of right section (m ²)	89.1
	Surface area of left section (m ²)	89.1
	Total heat loss through Cooling zone (kw)	74.86
d	Drying Zone	
	Average surface temperature of top section (°C)	19
	Average surface temperature of right section (°C)	18.5
	Average surface temperature of left section (°C)	17.1
	Surface area of top section (m ²)	533.6
	Surface area of right section (m ²)	261
	Surface area of left section (m ²)	261
	Total heat loss through Drying zone (kw)	43.14
	Total Surface Loss (kw)	414
	Heat loss (%)	14.21
8	Heat loss due to incomplete combustion	
	CO (ppm)	270
	CO ₂ (%)	3
	Heat loss (%)	0.89
Furnace Efficiency (%)		51.18

The thermal efficiency of tunnel kiln was calculated as 46.15% by direct method and 51.18% by indirect heat loss method. The achieved efficiency is in the range of typical efficiencies of 45-65% reported for tunnel brick kilns which indicates that the evaluated kiln is performing in the acceptable range for modern brick firing systems (Hasanbeigi et al., 2013; Madloul et al., 2011).

The heat loss analysis indicates that the highest loss is due to moisture evaporation from green bricks (18.33%), followed by heat losses from the surface (14.21%) and dry flue gas losses (7%). The highest surface heat loss (175.08 kW) was recorded in the firing zone, followed by the preheating zone (120.91 kW), while the cooling and drying zones

had lower losses among the kiln sections. The measured flue gas oxygen concentration of 17% (or ~425% excess air) indicates a high excess air supply and possible air leakage into the kiln system. This increases the flue gas heat losses and reduces the effective thermal efficiency of the kiln. Thus, improved kiln efficiency and SEC could be achieved with better combustion control and lesser excess air.

4.4 Financial evaluation

The financial evaluation was conducted to assess the economic viability and sustainability of the tunnel brick kiln project in the long term. The basic financial data were obtained from the plant records, management interviews & meeting, operational cost statements, capital investment, variable production costs, maintenance costs, electricity consumption, labor charges and selling price of bricks. The secondary data such as discount rate, project life and market assumptions were based on the prevailing economic conditions and industry standards.

The collected data were used to develop cash flow models for different production scenarios. Financial performance indicators such as IRR, and Discounted Payback Period were then calculated to determine project profitability, investment recovery time, and sensitivity to production capacity utilization. The financial parameter is shown as in Table 4.5.

Table 4.5: Financial parameters of tunnel kiln

S.N	Variables	Details	
1	Capital cost	Initial Investment	NPR 45,000,000
2	Variable costs	Fuel cost	NPR 4.56 per brick
		Electricity	NPR 0.54 per brick
		Labor cost	NPR 0.6 per brick
		Soil cost	NPR 1.5 per brick
		Other cost	NPR 3.42 per brick
3	Fixed cost	Annual Maintenance cost	NPR 1,000,000
4	Total Variable cost	NPR 10.62 per brick	
5	Revenue	NPR 19 per brick	
6	Life period (N)	20 years	
7	Discount Rate (i)	11.6 %	
8	No Production	3rd, 4th and 5th month of every year	
9	Cost during No production months	NPR 80,000 (Mainly Electricity)	

A financial scenario analysis was conducted by evaluating different production capacities ranging from 18% to 100% of maximum plant capacity (150,000 bricks/day). The financial scenario analysis can be tabulated as Table 4.6;

Table 4.6: Financial scenario analysis

S. N	Scenario	Capacity Utilization (%)	Annual Production (Million Bricks)	Payback Period (Years)	IRR (%)	Financial Feasibility
1	Very Low Production	18%	7.4	Not Achieved	8.9	Not Financially Feasible
2	Minimum Operating Level	21.6%	8.9	20	11.6	Break-even
3	Medium Production	30%	12.4	9.2	17.5	Profitable
4	Current Operating Level (BAU)	40.32%	16.6	5.8	24.2	Very Profitable
5	Increased Production	50%	20.6	4.4	30.4	Highly Profitable
6	High Production	75%	30.9	2.7	45.8	Highly Attractive Investment
7	Full Production Capacity	100%	41.3	1.9	61.2	Extremely Profitable

The results show that the financial viability increases significantly with the increase in production. At very low production levels (capacity utilization of 18%) the project does not seem financially feasible, as the IRR is only 8.9% and the payback period is not reached within the project lifetime. Production with a capacity utilization of about 21–22% is approaching the break-even point with a long payback period of 20 years and an IRR of 11.6%.

Beyond about 30% capacity utilization the plant is clearly profitable, with the payback period decreasing to 9.2 years and the IRR increasing to 17.5%. The financial

performance improves further to 40.32% at the current operating level with a payback of 5.8 years and an IRR of 24.2% which indicates a very profitable operation.

At higher levels of production (50%–100% capacity utilization) the project exhibits a strong financial performance with short payback periods (4.4 to 1.9 years) and much higher IRR values (30.4% to 61.2%) rendering the investment highly attractive. Overall trend points to the need to maintain higher production levels for ensuring economic sustainability and project profitability.

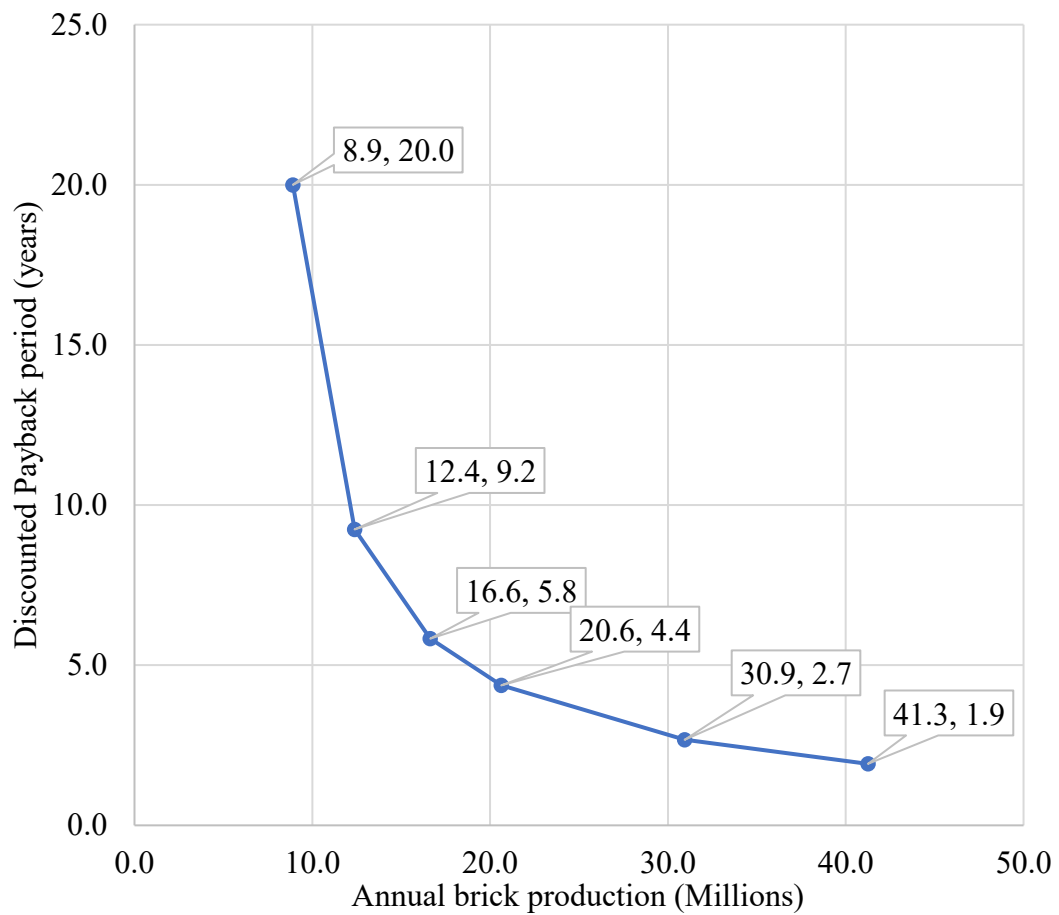


Figure 4.1: Payback period Vs Annual brick production

The Figure 4.1 presents the relationship between annual brick production and the discounted payback period. The results show a clear strong inverse and nonlinear relation between production level and payback period. At low production levels (9 million bricks/year) the discounted payback period is very high (about 20 years) which means poor financial performance and slow capital recovery.

As production increases to some 12 million bricks per year the DPP drops sharply to about 9 years, a major improvement in financial viability. As production keeps on increasing, DPP continues to fall fast. The DPP decreases to ~5.8–4.4 years at medium production levels (~16–21 million bricks per year) showing improved economic performance and faster recovery of the investment.

The DPP decreases even further at higher levels of production (around 30-41 million bricks per year) to about 2.7-1.9 years depicting a very high rate of capital turnover and high rate of investment appeal.

This nonlinear downward sloping trend in the figure confirms the strong negative relationship between production capacity and the discounted payback period, which emphasizes that, high production levels greatly enhance financial viability of the project.

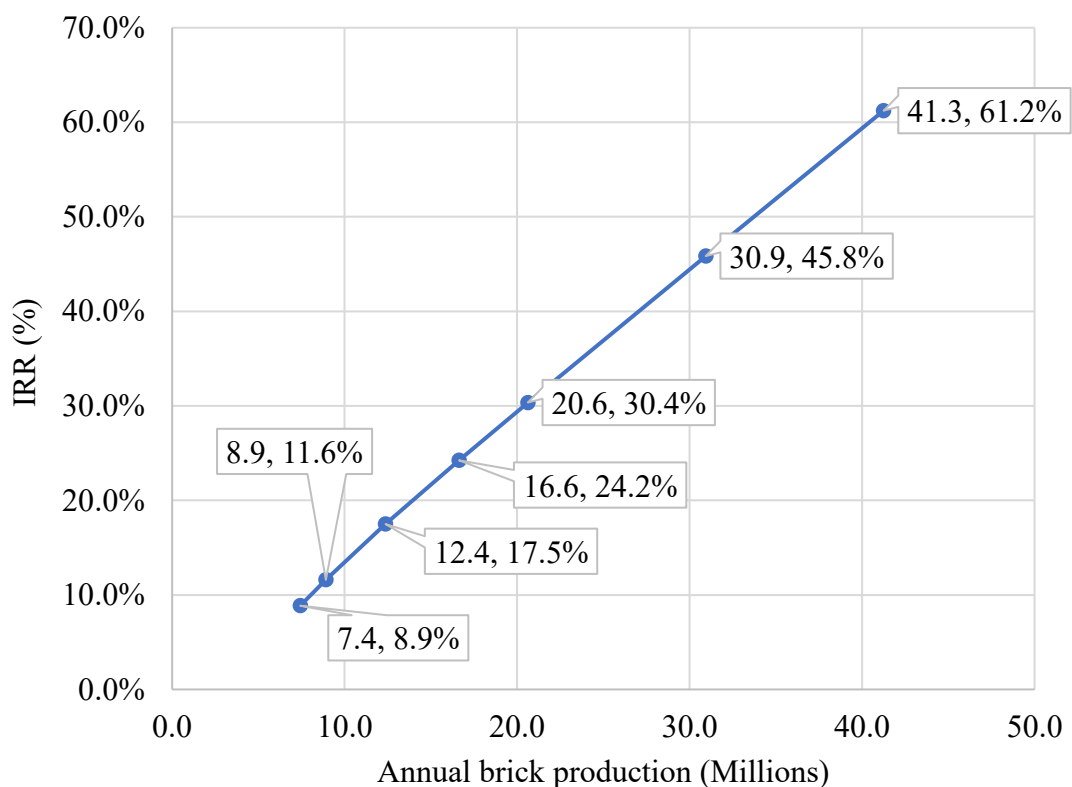


Figure 4.2: IRR Vs Annual brick production

The Figure 4.2 illustrates the relationship between annual brick production and the IRR. There exists a good positive and almost linear association between production capacity

and IRR. At low levels of production (approximately 7-9 million bricks annually), the IRR is relatively low (as it ranges between approximately 8.9% to 11.6%).

With a production of about 12 million bricks per year, the IRR is projected to be significantly higher at around 17.5%, which indicates an evident financial feasibility. Additional growth in production results in significant growth in the IRR up to about 24.2% to 30.4% at medium production levels (around 16-21 million bricks per year) which indicates good financial performance.

At high production levels (more than 30 million bricks annually), the IRR further rises to about 45.8% and to about 61.2% at full production capacity, and this implies a very high level of profitability and a high level of investment attractiveness.

The positive straight-line trend confirms the good direct relationship between the volume of production and the investment return as it indicates that the higher the production level, the greater the financial viability of the project.

4.5 Emission evaluation

The emission performance of the tunnel brick kiln was measured using two complementary methods: (i) stack gas measurements and (ii) Fuel-based analytical estimation. Such a mixture of approaches offers a more detailed evaluation of pollutant emissions and carbon intensity.

4.5.1 Stack gas measurements analysis

Stack gas emission measurements were carried out using a portable flue gas analyzer (E4500-N model) under steady operating conditions. The measured parameters are included in the Table 4.7.

Table 4.7: Primary stack parameters

S. N	Description	Value	Nepal Standard
1	CO ₂ (%)	3	-
2	C0 (ppm)	270	-
3	O ₂ (%)	17	-
4	Flue gas Temperature (°C)	52	-
5	SPM (Normalized at 4% CO ₂) (mg/Nm ³)	68.9	100
6	Colour of Smoke in Stack	Gray	-
7	Height of Stack (m)	11.7	10

S. N	Description	Value	Nepal Standard
8	Stack Velocity (m/s)	6.1	-
9	Diameter of chimney at Sampling port (m)	1.13	-
10	Area at chimney at Sampling port (m ²)	1	-
11	NO (ppm)	70	-
12	NO ₂ (ppm)	6	-
13	NO _x (ppm)	76	-
14	CH ₄ (ppm)	3	-
15	S ₀ 2 (ppm)	118.34	-

The CO₂ and CO emission estimation by stack method is calculated as shown in Table 4.8, which shows the emission performance of the tunnel kiln based on stack gas parameter measurements. A CO₂ mass emission rate of 0.35 kg/s was obtained from the calculated flue gas flow rate of 6.1 m³/s. An estimated 8530.1 tons of CO₂ were released annually due to the kiln's 275 days of operation. It was discovered that the associated CO₂ emission intensity was 507.5 kg CO₂ per 1000 bricks, or 203.35 g CO₂ per kilogram of burnt bricks.

In a similar vein, the measured CO concentration produced a CO mass emission rate of 0.00187 kg/s, resulting in a yearly CO emission of 44.5 tons and an emission intensity of 2.67 kg CO per 1000 bricks (i.e., 1.07 g CO/kg burnt bricks).

These findings show that, although CO emissions are still quite low, CO₂ is the tunnel kiln's primary emission component, while CO emissions remain comparatively low, indicating near-complete combustion.

Table 4.8: CO₂ and CO emission estimation by stack method

S. N	Description	Value
1	Flue flow rate (m ³ /s)	6.1
2	CO ₂ volumetric flow rate (m ³ /s)	0.18
3	CO ₂ mass flow rate (kg/s)	0.35
4	Annual CO ₂ emission (275 operating days) (tons/year)	8530.1
5	CO ₂ emission intensity (kg CO ₂ /1000 Bricks)	507.5
6	CO ₂ emission intensity (g CO ₂ /kg fired Bricks)	203.35
7	CO Mass emission rate (kg/s)	0.00187
8	Annual CO emission (tons/year)	44.5
9	CO emission intensity (kg CO/1000 bricks)	2.67
10	CO emission intensity (g CO/kg fired bricks)	1.07

The obtained CO₂ emission intensity (203 g CO₂/kg fired bricks) lies within the typical international range reported for fired brick production (200–350 g CO₂/kg bricks), depending on kiln technology and fuel type (Hasanbeigi et al., 2013; Climate & Clean Air Coalition, 2016). The relatively low CO emission intensity further indicates near-complete combustion compared to traditional brick kiln technologies, which often exhibit higher CO emissions due to incomplete combustion.

4.5.2 Fuel-based analytical estimation

The Table 4.9 presents the estimation of CO₂ emissions from the tunnel kiln using the fuel-based calculation method (i.e. inventory method). The annual fuel usage was calculated using the daily fuel consumption and the number of operating days. The carbon mass fraction and oxidation factor were then used to determine the CO₂ emission, taking into consideration the portion of carbon that was completely oxidized during burning. The CO₂ emission intensity was calculated to be 529.8 kg CO₂ per 1000 bricks based on the yearly brick production.

Table 4.9: Fuel-based CO₂ emission estimation (inventory method)

S. N	Description	Value
1	Daily fuel consumption (kg/day)	11890
2	Operating days of Kiln (day/year)	275
3	Oxidation factor	0.98
4	Annual fuel consumption (tons/year)	3269.75
5	Annual CO ₂ emission due to fuel consumption (tons/year)	8811.97
6	CO ₂ emission intensity (kg CO ₂ /1000 Bricks)	529.8
7	CO ₂ emission intensity (g CO ₂ /kg fired Bricks)	211.9

Based on fuel consumption, the tunnel kiln emitted approximately 212 g CO₂ per kg of fired brick, which is considerably lower than the emission levels reported for Nepal's traditional FCBTK technology (≈450–500 g CO₂/kg bricks). The obtained value is also close to improved kiln benchmarks of around 200–250 g CO₂/kg bricks and lies within the typical international range reported for fired brick production (200–350 g CO₂/kg bricks), depending on kiln technology and fuel characteristics (Hasanbeigi et al., 2013; Climate and Clean Air Coalition, 2016)

To ensure consistency and dependability of results, the tunnel kiln's emissions were evaluated using a fuel-based inventory approach in addition to stack gas measurements. The fuel-based technique predicted 8,811.97 tons of CO₂ year, with an emission

intensity of 529.8 kg CO₂ per 1000 bricks, whereas the stack measurement method estimated 8,530.1 tons of CO₂ annually, or 507.5 kg CO₂ per 1000 bricks. The relatively close agreement between the two approaches indicates reasonable consistency in the emission estimation and validates the reliability of the results.

4.5.3 GHG emission evaluation

GHG emissions are the gases released into the atmosphere which contribute to the greenhouse effect and global warming. These emissions are mainly due to the combustion of fuels such as coal in the firing process of brick kilns. The major greenhouse gases emitted include carbon dioxide (CO₂), methane (CH₄), carbon monoxide (CO) and nitrous oxide (N₂O). Among these, CO₂ is the dominant component due to the oxidation of carbon in fuel. To assess the overall climate impact, emissions of different gases are commonly converted into carbon dioxide equivalent (CO₂e) using their respective Global Warming Potential (GWP) values provided by the IPCC.

The GHG emission from tunnel brick kiln is calculated as shown in Table 4.10.

Table 4.10: GHG emissions from tunnel brick kiln

S. N	Description	Value (tons/year)	GWP-100	CO ₂ Equivalent (tons/year)
1	CO ₂	8530.1	1	8,530.1
2	CO	48.9	-	-
3	NO	13.82	-	-
4	NO ₂	1.81	-	-
5	NO _x	15.63	-	-
6	CH ₄	0.32	29.8	9.536
7	S ₀ ₂	50	-	-
Total GHG emission (CO ₂ e)				8,539.636

The dominant contribution to total GHG emissions was CO₂, with an annual emission of 8,530.1 tons/year, which directly corresponds to the largest share of the total CO₂ equivalent emissions. The gases like CO and CH₄ also contributed to the total climate impact when converted to CO₂ equivalent. The CH₄ emissions of 0.32 tons/year contribute 9.54 tons CO₂e per year due to its higher global warming potential (GWP = 29.8).

The total GHG emission of the tunnel kiln was estimated to be 8,539.636 tons CO₂e per year, indicating that CO₂ from fuel combustion is the primary contributor to climate impacts, while other gases contribute only marginally.

It is important to note that NO, NO₂, NO_x and SO₂ were not included in the CO₂ equivalent calculation as these gases are not normally assigned standardized GWP values in GHG accounting frameworks such as the IPCC guidelines but are classified mainly as air pollutants rather than greenhouse gases.

4.6 CFD-Simulated Temperature Profiles of Hot Gases under Stoichiometric, Fuel-Rich, and Excess Air Combustion Conditions

4.6.1 For coal combustion

The Figure 4.3 presents the variation of hot gas temperature with heating time for stoichiometric, fuel-rich, and excess air coal combustion conditions. The most efficient combustion performance is demonstrated by the stoichiometric scenario, which exhibits

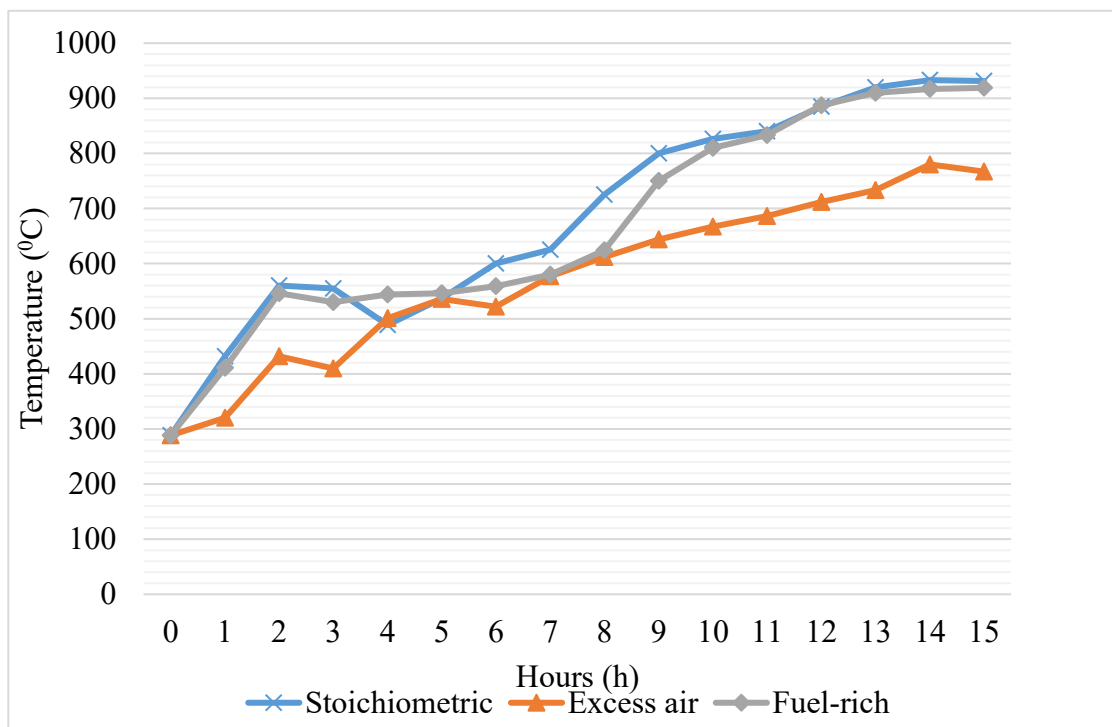


Figure 4.3: Temperature profile of hot gases under coal combustion at different air–fuel conditions

the highest temperature development for the majority of the heating period and reaches the maximum ultimate temperature. Due to incomplete combustion brought on by limited oxygen supply, the fuel-rich example exhibits a similar trend but stays

somewhat lower. On the other hand, because excess air dilutes hot gases and lowers the effective heat available for temperature rise, the excess air situation exhibits the lowest temperature profile.

The Figure 4.4 illustrates the CFD-simulated temperature distribution within the brick arrangement under stoichiometric coal combustion. The majority of the brick stack has a high and largely consistent temperature field, with temperatures close to 930°C. Strong heat transport from the hot gases to the brick surfaces and effective combustion are indicated by this. According to the temperature contour, stoichiometric operation offers the best thermal conditions for reliable and efficient brick heating.

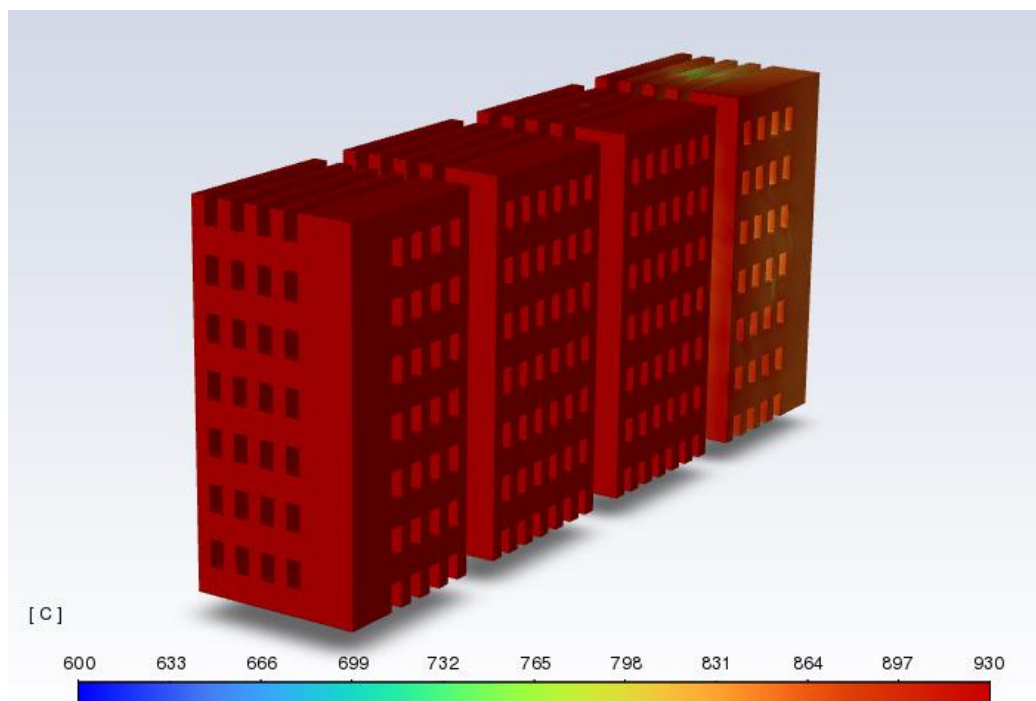


Figure 4.4: Temperature contour of brick arrangement under stoichiometric coal combustion

The Figure 4.5 shows the temperature distribution within the brick arrangement for the fuel-rich coal combustion condition. With peak temperatures of about 910°C, the total temperature level is still high but marginally lower than in the stoichiometric case. This decrease can be explained by a restricted supply of oxygen which prevents full combustion and reduces the amount of heat released during combustion. The contour

indicates that the brick stack has been heated significantly, but to a somewhat lower thermal intensity than under stoichiometric conditions.

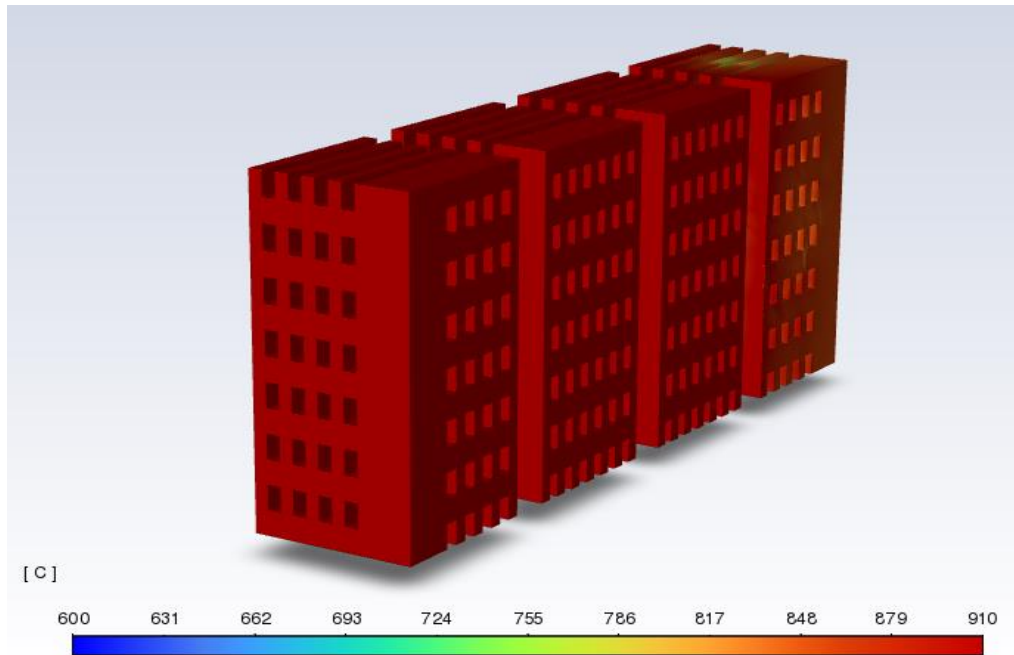


Figure 4.5: Temperature contour of brick arrangement under fuel-rich coal combustion

The Figure 4.6 presents the temperature contour for the brick arrangement under excess air coal combustion. Compared with the stoichiometric and fuel-rich cases, this

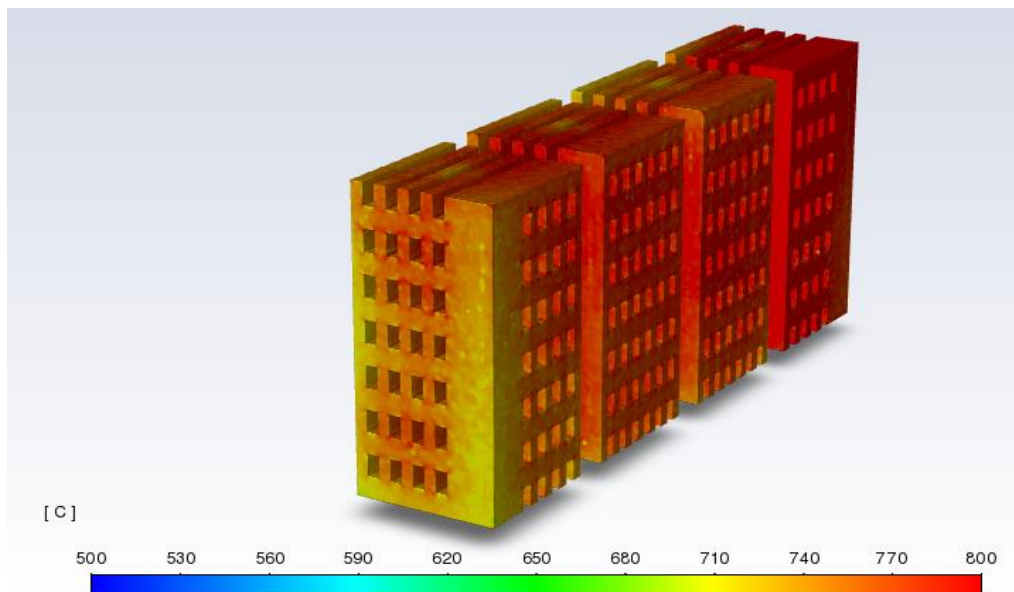


Figure 4.6: Temperature contour of brick arrangement under excess air coal combustion

condition produces a distinctly lower temperature field, with maximum temperatures

around 770–800°C. The lower thermal degree is mainly attributed to the dilution effect of more air which absorbs part of the emitted heat and reduces the gas temperature. Thus, the brick stack is heated less which means the operation of excess air in the tunnel kiln is less thermally efficient in coal burning.

4.6.2 For natural gas combustion

The Figure 4.7 presents the variation of hot gas temperature with heating time under stoichiometric, fuel-rich, and excess air conditions for natural gas combustion. The

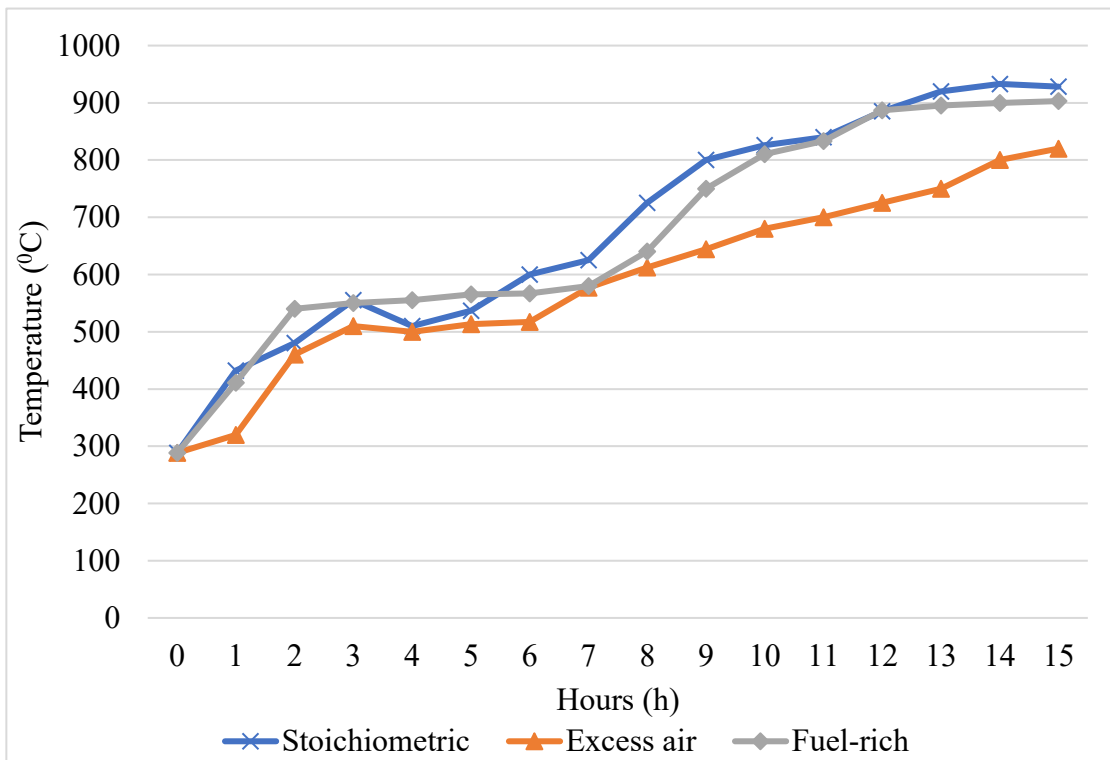


Figure 4.7: Temperature profile of hot gases under natural gas combustion at different air–fuel conditions

maximum final temperature is observed during the entire heating period in the stoichiometric case which means that the combustion is most efficient. The trend is similar for the fuel-rich case but the final temperature is slightly lower due to incomplete combustion because of lack of oxygen. Excess air, on the other hand presents the lowest temperature profile as it dilutes the hot gases and reduces the efficient heat available for temperature rise.

The Figure 4.8 illustrates the CFD-simulated temperature distribution within the brick arrangement under stoichiometric natural gas combustion. The temperature field across much of the brick stack is high and fairly uniform with temperatures near about 930°C. This indicates effective combustion and good heat transfer from the hot gases to the brick surfaces. The temperature contour indicates that stoichiometric combustion provides the best thermal conditions for efficient and uniform heating of bricks.

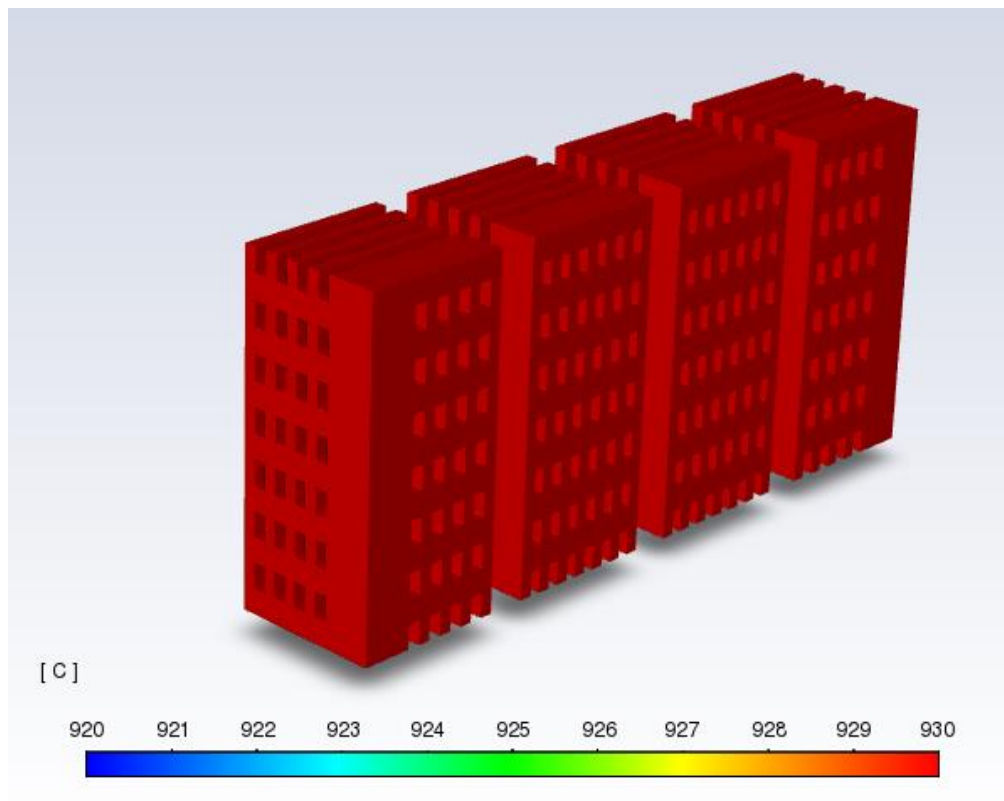


Figure 4.8: Temperature contour of brick arrangement under stoichiometric natural gas combustion

The Figure 4.9 shows the temperature distribution within the brick arrangement under fuel-rich natural gas combustion. The overall temperature level is high but a little lower than in the stoichiometric case with peak temperatures of about 905°C. Due to the limited oxygen supply, the complete combustion is not possible and the total amount of released heat decreases. However, the contour shows a considerable heating of the brick stack but the thermal intensity is a little lower than in the stoichiometric condition.

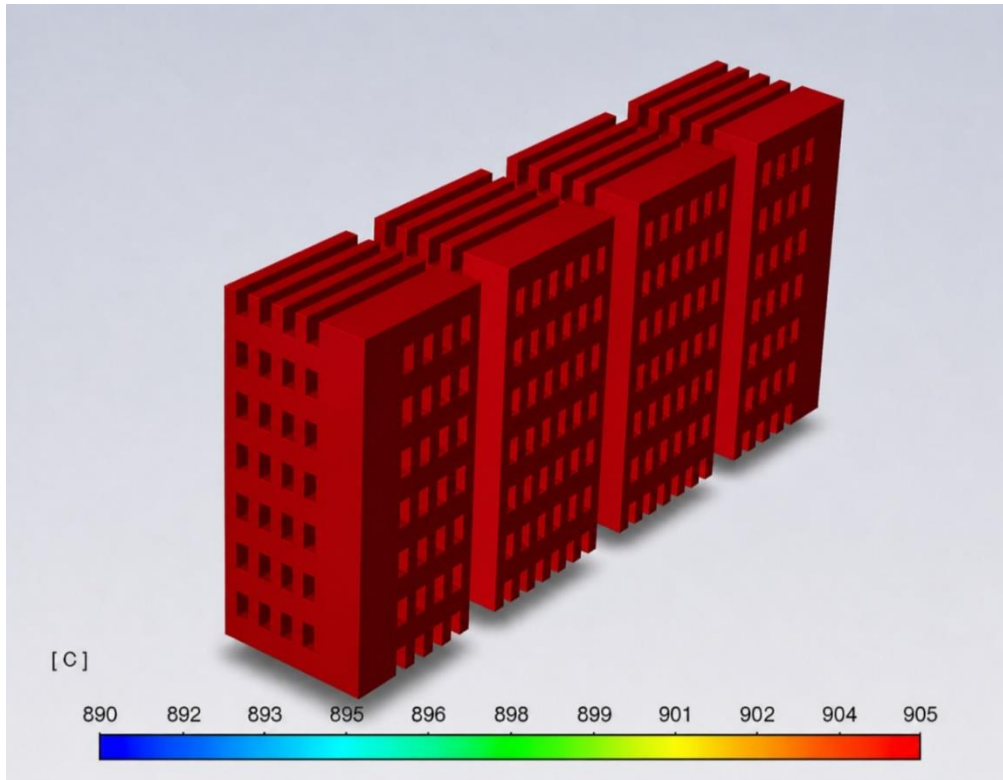


Figure 4.9: Temperature contour of brick arrangement under fuel-rich natural gas combustion

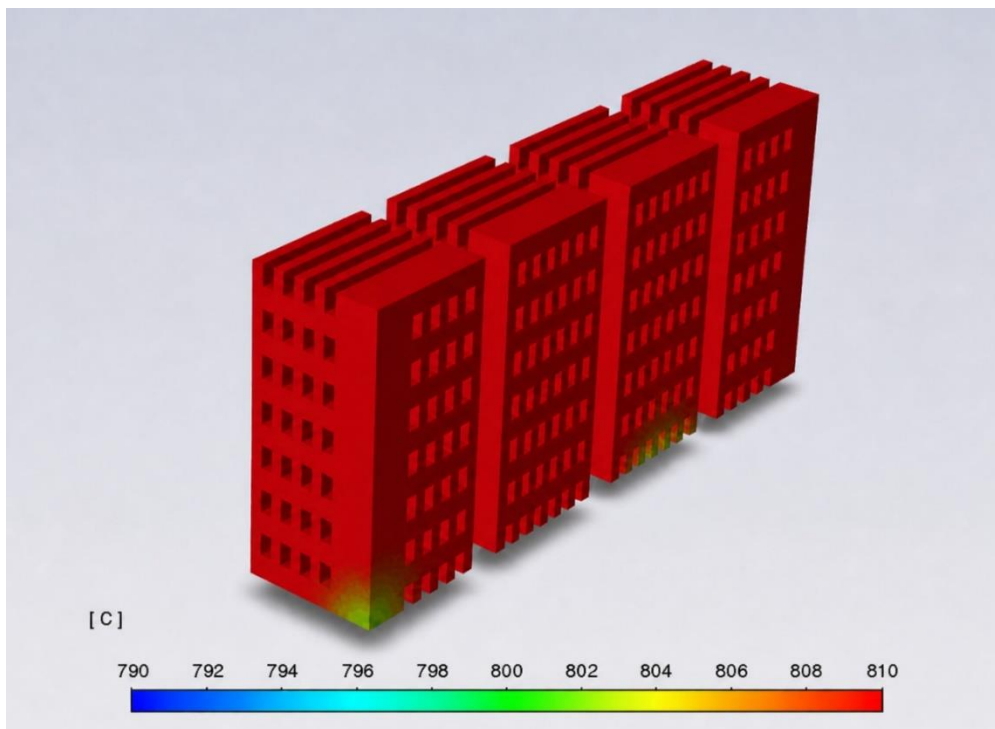


Figure 4.10: Temperature contour of brick arrangement under excess air natural gas combustion

The Figure 4.10 presents the temperature contour of the brick arrangement under excess air natural gas combustion. This condition creates a temperature field that is much lower than the stoichiometric and fuel-rich cases with maximum temperatures around 810°C. The gas temperature drops because extra air takes in some of the heat that is released. This lowers the thermal level. So, the brick stack doesn't get as hot which means that using too much air to burn natural gas in the tunnel kiln isn't as effective.

4.7 Energy, Emission and Cost Reduction

The thermal efficiency of tunnel kilns typically ranges from 50–65% for coal-fired systems and 65–80% for natural gas-fired systems due to differences in combustion characteristics and heat recovery. Based on this, efficiencies of 60% for coal and 75% for natural gas were assumed as representative values for practical kiln operation (International Energy Agency, 2007; Mançuhan & Küçükada, 2006; Hussnain et al., 2021). The cost of natural gas including the Customs duty on LNG imports in Nepal of 15% and VAT of 13% on CIF plus duty is NPR 65 as confirmed by Yogya Holding.

Table 4.11: Parameters used for Reduction

S. N	Description	Value	Unit
1	Useful Energy required for tunnel kiln (ideal case)	31,951.40	GJ/year
2	Coal kiln efficiency	60	%
3	Natural gas kiln efficiency	75	%
4	Price of Coal	25	NPR
5	Price of Natural gas	65	NPR
6	LCV of Coal	21.09	MJ/kg
7	LCV of Natural gas	50	MJ/kg

The Table 4.11 presents the key input parameters used to compare coal-fired and natural gas-fired tunnel kilns on an annual basis. It takes into account the kiln's practical energy requirements, presumptive thermal efficiency, fuel costs, and the lower calorific values of natural gas and coal. The necessary fuel input, yearly fuel consumption, and operational costs for each fuel option are estimated using these figures. The information demonstrates that although though natural gas costs more per unit, its better calorific value and kiln efficiency can lower the total amount of fuel used.

The calculation of energy, emission and cost savings can be calculated as shown below in Table 4.12.

Table 4.12: Energy, Emission and Cost Saving

Reduction	S. N	Parameters	Value	Unit
Energy Reduction	1	Energy required for coal kiln	53,252.34	GJ/year
	2	Energy required for natural gas kiln	42,601.87	GJ/year
	3	Energy reduction	10,650.47	GJ/year
	4	Energy saving %	20	%
Emission Reduction	5	Mass of coal required	2,525.004	tons/year
	6	Mass of natural gas required	852.037	tons/year
	7	CO ₂ emission from coal kiln	6,804.89	tons/year
	8	CO ₂ emission from natural gas kiln	2,343.10	tons/year
	9	Emission reduction	4,461.78	tons/year
	10	Emission saving %	65.57	%
Cost Reduction	11	Total annual cost for coal	63,125,103.84	NPR/year
	12	Total annual cost for natural gas	55,382,431.10	NPR/year
	13	Cost reduction	7,742,672.737	NPR/year
	14	Cost saving %	12.27	%

The Table 4.12 shows that replacing coal with natural gas in the tunnel kiln gives clear annual benefits in energy, emissions, and cost.

In terms of energy, the kiln's annual requirement decreases from 53,252.34 GJ/year for coal to 42,601.87 GJ/year for natural gas, resulting in an energy reduction of 10,650.47 GJ/year, or about 20% savings. For emissions, fuel switching reduces annual CO₂ emissions from 6,804.89 tons/year to 2,343.10 tons/year, giving a large reduction of 4,461.78 tons/year, which is about 65.57% lower than coal. Economically, the annual fuel cost drops from NPR 63.13 million/year for coal to NPR 55.38 million/year for natural gas, leading to a cost reduction of about NPR 7.74 million/year, or about 12.27% savings. The results show that natural gas is a better fuel choice for tunnel kiln operation than coal because it is more efficient, cleaner, and cheaper.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study assessed the energy efficiency, emission profiles, economic viability, and CFD-based combustion dynamics of a tunnel brick kiln in Nepal, along with the feasibility of fuel substitution. The analysis leads to the following conclusions;

1. Energy performance: The calculated thermal efficiency was 46.15% (direct method) and 51.18% (indirect method). This is in line with the range of 45–65% that has been reported for tunnel kilns. The total SEC was 1.72 MJ/kg of fired brick and the thermal SEC was 1.66 MJ/kg which shows that the system worked well. The measured flue gas oxygen concentration of 17% on the other hand suggests that there is a lot of extra air in the system. This leads to higher dry flue gas losses and a slightly higher SEC.
2. Emission performance: The annual carbon dioxide emissions were calculated using the stack method as 8,530.1 tons whereas the value calculated using the fuel consumption method was 8,811.97 tons. The carbon monoxide emission intensity was quite low (1.07 g CO/kg fired brick), indicating nearly complete combustion. GHG emissions from the tunnel kiln were found to be 8,539.636 tons per year.
3. Financial performance: The financial analysis showed a high dependency on production capacity utilization for the viability of the project. Low production levels in terms of capacity utilization (around 18%) resulted in non-viability of the project. The breakeven point happens when capacity utilization is around 21-22% (equivalent to about 8.9 million bricks produced yearly). At this level, the IRR of the project was estimated at 11.6% while the payback period was estimated at 20 years. Profitability of the project starts at capacity utilization higher than 30%. Payback period will fall sharply beyond this point. For full capacity utilization (41.3 million bricks/year), payback period would be reduced to 1.9 years with an IRR of about 61.2%.
4. CFD: The transient CFD analysis indicated that stoichiometric combustion yielded the highest and most efficient temperature progression for both coal and natural gas while fuel-rich combustion resulted in marginally lower

thermal performance, and excess-air combustion generated the lowest temperature field due to dilution by surplus air. This confirms that controlling the air in the kiln was very important for making it work better and heating it up more effectively.

5. Fuel Switching: The natural gas is an ideal fuel for a tunnel brick kiln. It can save energy consumption annually by 20%, carbon dioxide emissions by 65.57% annually, and fuel cost annually by 12.27%. The conversion from coal to natural gas has improved energy utilization, environment emissions, and economics
6. Integrated assessment: The results reveal strong interdependencies between the energy performance, emissions, combustion conditions and financial viability. Improved combustion control, reduced excess air and use of cleaner fuels can help to improve the operation of the tunnel brick kiln in Nepal.

5.2 Recommendations

Based on the findings, the following recommendations are proposed:

- Combustion optimization: Minimize excess air and losses due to dry flue gas. It is important to practice normal adjustment of the air-fuel ratio to ensure near-stoichiometric combustion and the improvement of thermal efficiency
- Moisture control: Advanced drying methods of green bricks to minimize heat losses from moisture content
- Capacity utilization: Keep production at levels above break-even to keep the business sustain
- Fuel substitution: To be able to evaluate and consider the phased substitution of coal by natural gas or other renewable energy sources in future development of the tunnel kiln as an important energy saving, emissions reduction, and cost reduction as highlighted in our study
- Future research: More comprehensive scale-up of studies to full scale CFD optimization of burner arrangement, airflow distribution, retention time and temperature uniformity and validation with more extensive field measurements
- Policy-level recommendation: The government authorities need to create national standards of the SEC, thermal efficiency, and the emission intensity of the brick kilns in Nepal and incorporate them into the climate mitigation framework of Nepal

through its NDC. Improvement of policies and promotion of energy efficient technologies like kilns will help to mitigate the contribution of brick industry in greenhouse gas emission and to achieve the long-term goal of decarbonization in Nepal

These results shows that the technology related to tunnel brick kilns provide a good approach for better energy efficiency, less emission intensity and economically strong performance. This could allow the brick sector to make positive impact towards climate change mitigation strategies by adopting proper policies consistent with the Nepal's NDC. Overall, this research can offer valuable conclusions for improving the brick industry in Nepal.

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APPENDIX

Appendix-A: Site visit and data collection photographs



During site survey



Green bricks entrance to drying Zone



Stacking machine



Soil storage for mixing with coal



Fired bricks



Stacking of green bricks



Coal storage for mixing with soil



Flue gas analyzer



Measurement of surface temperature



Kiln Temperature Monitoring system



Coal+ Saw dust entering hole



Kiln Area



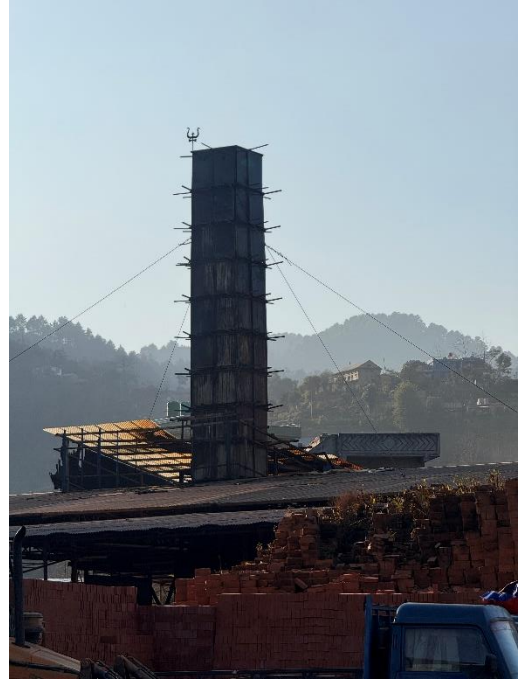
Firing Zone



Tunnel Brick Kiln Site



Cake formation



Chimney tower



Fired bricks coming out from cooling zone



Storage of fired bricks



Clay extruder machine

Appendix-B: Clay composition

S. N	Composition	Range (%)
1	Silicon dioxide (SiO ₂)	50-60
2	Aluminum oxide (Al ₂ O ₃)	20-30
3	Iron (III) oxide (Fe ₂ O ₃)	5-8
4	Calcium oxide (CaO)	2-5
5	Magnesium oxide (MgO)	< 1
6	Organic matter	Not any traces

Appendix-C: Ultimate analysis of Raniganj coal

S. N	Components	Value (%)
1	Carbon	54.9
2	Hydrogen	5.0
3	Nitrogen	2
4	Silicon	0.38
5	Oxygen	10.7

Appendix-D: Preheating zone temperature readings

Reading No.	Top Section (°C)	Left Section (°C)	Right Section (°C)
1	18.0	14.5	11.2
2	24.5	22.8	19.6
3	36.2	31.4	28.9
4	42.8	39.7	35.4
5	33.5	36.1	34.8
6	37.0	29.5	33.9
Average	32.0	29.0	27.3

Appendix-E: Firing zone temperature readings

Reading No.	Top Section (°C)	Left Section (°C)	Right Section (°C)
1	31.5	20.0	17.5
2	38.0	26.5	24.0
3	44.5	31.0	28.5
4	51.0	36.5	33.0
5	49.5	35.0	34.5
6	46.5	37.0	33.5
Average	43.5	31.0	28.5

Appendix-F: Cooling zone temperature readings

Reading No.	Top Section (°C)	Left Section (°C)	Right Section (°C)
1	15.5	12.0	13.5
2	20.0	17.5	18.0
3	25.5	21.0	22.5
4	31.0	27.5	28.0
5	33.5	28.0	30.5
6	30.5	26.0	27.3
Average	26.0	22.0	23.3

Appendix-G: Drying zone temperature readings

Reading No.	Top Section (°C)	Left Section (°C)	Right Section (°C)
1	9.5	8.0	8.5
2	14.0	12.5	13.0
3	18.5	16.8	18.0
4	23.5	20.5	22.0
5	26.0	22.0	24.5
6	22.5	22.8	25.0
Average	19.0	17.1	18.5

Appendix-H: IOEGC acceptance letter



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त्रिभुवन विश्वविद्यालय
TRIBHUVAN UNIVERSITY
इंजिनियरिङ्ग अध्ययन संस्थान
INSTITUTE OF ENGINEERING

पुल्चोक क्याम्पस
PULCHOWK CAMPUS

5-521260
5-521611
5-522104
5-522809

पुल्चोक, ललितपुर ।
Pulchowk, Lalitpur



Date: May 8, 2026

To Whom It May Concern:

This is to certify that the paper titled "*Energy, Emission and Financial Assessment of a Tunnel Brick Kiln in Nepal: A Case Study*" (Submission ID #850), with **Basil Sharma** as the first author, was accepted through the peer-review process and has been presented at the 18th IOE Graduate Conference, organized at Pulchowk Campus, Lalitpur, Nepal, from May 7 to 9, 2026.

Please note that inclusion of the accepted manuscript in the conference proceedings is contingent upon timely compliance with any further editorial requirements during the publication process.

Prof. Sangeeta Singh
Convener
18th IOE Graduate Conference



Appendix-I: Plagiarism report

Basil Sharma

Integrated Energy, Emissions, Financial, and CFD-Based Assessment of a Tunnel Brick Kiln in Nepal

Tribhuvan University

Document Details

Submission ID
tmsid:311758781517

87 Pages

Submission Date
May 8, 2026, 5:08 AM GMT+5:45

21,021 Words

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May 8, 2026, 5:11 AM GMT+5:45

109,535 Characters

File Name
Thesis Report by Basil Sharma, - for plagiarism.pdf

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Appendix-J: AI report

Basil Sharma

Integrated Energy, Emissions, Financial, and CFD-Based Assessment of a Tunnel Brick Kiln in Nepal

Tribhuvan University

Document Details

Submission ID
tmsoid:3117587781517

87 Pages

Submission Date
May 8, 2026, 5:08 AM GMT+5:45

21,021 Words

Download Date
May 8, 2026, 5:13 AM GMT+5:45

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Non-qualifying text, such as bullet points, annotated bibliographies, etc., will not be processed and can create disparity between the submission highlights and the percentage shown.

