Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2026, Volume 14, Issue 2, 1130664

Original Research Article

Energy Transition Potential in Brick Industries: A Simulation Based Assessment of Zigzag Kilns

Kshitiz Ghimire[1], Hari Bahadur Darlami*[1], Sanjaya Neupane[1], Ajay Kumar Jha[1]

[1]Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal

e-mail: kshitiz.ghimire97@gmail.com

Cite as: Ghimire, K., Darlami, H. B., Neupane, S., Jha, A. K., Energy Transition Potential in Brick Industries: A Simulation Based Assessment of Zigzag Kilns, J.sustain. dev. energy water environ. syst., 14(2), 1130664, 2026, DOI: https://doi.org/10.13044/j.sdewes.d13.0664

ABSTRACT

Brick manufacturing in Nepal relies heavily on coal and biomass mixtures, resulting in high energy use and significant air pollution. This study investigates the energy-saving potential and environmental implications of fuel substitution in brick kilns, focusing on coal, biomass, and natural gas. A combination of experimental data collection and steady-state computational fluid dynamics simulations was employed to analyse thermal performance, airflow characteristics, and pollutant formation along the kiln. The study evaluated the effect of varying inlet air velocities on fuel combustion, excess air, and kiln efficiency. For coal and biomass, inlet air velocities ranging from 4.5 to 6.1 m/s were analysed, while natural gas was studied as an alternative fuel for coal and biomass mixture under optimum condition. The results revealed that excess air in the combustion zone significantly influences the thermal efficiency, with coal and biomass showing higher excess air levels compared to natural gas. The kiln efficiency was determined using indirect method highlighting the potential for energy savings and emission reduction through optimized air supply and fuel transition. The findings provide quantitative insights into the benefits of energy transition in brick industries, demonstrating that adopting cleaner fuels and controlling excess air can improve efficiency and reduce environmental impact.

KEYWORDS

Brick kiln efficiency, thermal performance, excess air, Computational Fluid Dynamics

INTRODUCTION

Brick manufacturing is an energy-intensive industry and a major source of air pollution throughout the world. South Asia accounts for 21% of the global brick production, making it the second largest producer after China where traditional kiln technologies dominate. The technologies still remain unchanged over a longer time period [1]. A study done by International Centre for Integrated Mountain Development (ICIMOD) in 2019 estimated that the brick industries in Nepal are responsible for the emission of 5.1 Metric Tons of CO_2 emissions per year [2]. A total of 465,220 tons of coal equivalent per year is used as source of fuel for brick sector in Nepal producing total emission of 1,299,065 tons of CO_2 equivalent [3].

Traditional firing technologies in brick kilns are highly inefficient, leading to excessive fuel consumption and increased carbon emissions [4]. Improving kiln efficiency is therefore critical for reducing energy use and minimizing harmful exhaust gases. This study aims to evaluate energy-saving measures, assess the feasibility of cleaner technologies, and propose practical solutions that balance environmental sustainability with economic viability. The outcomes are expected to provide useful insights for policymakers and support the shift toward more sustainable practices in the brick industry.

LITERATURE REVIEW

Brick firing is the most energy-intensive stage of brick production, accounting for the highest operational costs and environmental impacts. In Nepal, the sector consumes an estimated 465,220 tons of coal equivalent annually, with coal contributing about 82% of total fuel use, followed by diesel (8.9%) and firewood (8.7%), while rice husk, bagasse, and wood chips are used to a lesser extent [3]. This reliance on fossil fuels makes brick manufacturing one of the largest sources of greenhouse gas (GHG) emissions in the country.

Different kiln technologies are employed in South Asia, including clamp kilns, fixed-chimney Bull's Trench Kilns (FCBTKs), zigzag kilns, and vertical shaft brick kilns (VSBKs) [5]. Among them, traditional FCBTKs remain dominant, though they are also the most polluting. Zigzag kilns, which direct flue gases through staggered brick arrangements, achieve 10–20% higher fuel efficiency and substantially lower emissions compared to FCBTKs [6]. Nevertheless, their performance often suffers due to inconsistent construction and poor combustion control. Emission inventories in Nepal further show that FCBTKs release over 923,000 tons of CO_2-equivalent annually, while zigzag kilns contribute about 216,000 tons, with other technologies such as VSBK, Hoffmann, and tunnel kilns producing comparatively less [3].

The drying of green bricks plays a crucial role to prevent the formation of cracks, and studies recommend air or shade drying for 24 to 48 hours, followed by controlled heating at 50-110 °C until a constant weight is achieved [7], [8]. Slow and uniform moisture removal at this stage helps avoid structural deformation before firing [9]. For clays found inside Kathmandu valley, mineralogical transformations such as the formation of spinel and primary mullite occur between 900 °C and 1100 °C, suggesting that optimum firing lies within 900–1050 °C to achieve high strength and reduced porosity [10], [7]. Increasing the firing temperature and extending the soaking period enhances densification, compressive strength, and decreases water absorption as determined by studies done in regional and international levels [9].

Comparative studies across South Asia reveal that induced-draft zigzag kilns (IDZK) and VSBKs consistently outperform FCBTKs in terms of both specific energy consumption (SEC) and pollutant control [5]. These kilns benefit from improved turbulence and heat recovery, which result in lower emissions of particulate matter, SO_2, and NO_x [11]. However, proper stacking, draft control, and regular maintenance remain critical, since fugitive emissions can offset the improvements gained at the stack [12], [13]. Gas-fired tunnel kilns have also demonstrated potential, with basic efficiency improvements such as heat-recovery and power factor correction delivering about 8% fuel savings and short payback periods [14]. Valdes et al. confirmed that the performance of artisan brick kilns can be improved through integration of mechanical fans, enhanced thermal insulation of kiln as well as automated control of operational activities [15]. Similarly, incorporating alternative materials having lower thermal conductivity along with proper insulation is also crucial for minimizing heat dissipation and maintaining stable temperature of the combustion zone [16]. The highest reported energy and emission performance identifies that coupling two kilns can increase energy efficiency to 77% from 60.66% and can reduce emissions by approximately 53.83% [17]. The employment of agricultural waste consisting 15% of pomegranate peel waste in the fuel achieved energy savings of 17.55% - 33.13% and CO_2 emission reductions of 7.50% - 24.50% [18]. Arora et al. evaluated pellets made from paddy straw as a partial substitute of coal using fuel blends consisting of pellets ranging from 10-30% and concluded that 20% of coal can be replaced with paddy straw pellets without any change in the kiln performance [19]. Broader decision-analytic studies confirm that technology conversion and fuel switching are the most effective pathways for reducing both environmental and health impacts from the brick industry [20], [21].

Computational Fluid Dynamics (CFD) has become an established tool to investigate the complex heat, mass and momentum transport processes within brick kilns that are difficult to measure in operational plants [22]. Simulation helps us to examine the internal kiln phenomena like detailed temperature distribution, fluid flow behaviour that are difficult to obtain through direct measurement [23]. The visualization of internal heat transfer and fluid flow behaviours inside the kilns using numerical simulations has enabled researchers in improving the design and operational behaviours of the kilns [24]. Several studies have used CFD to map temperature and velocity fields, identify flow recirculation and hotspots, and evaluate combustion and emission behaviour in different kiln types, Fixed Chimney (FCK), zigzag/tunnel and shuttle kilns providing actionable insights for design improvement and fuel saving [22], [25]. Tasnim et al. applied transient CFD under ANSYS Fluent to compare FCK and zigzag geometries and identified zones of flow separation and temperature non-uniformity that explain localized under-firing and excess fuel use [22]. Beyene et al. studied biogas-fired clay-brick kiln using CFD and demonstrated that alternative fuels and burner placements alter gas temperatures and combustion completeness, with implications for both emissions and energy use [26]. Recent studies have validated correlations for heat transfer and pressure drop in lattice brick settings [27], and transient CFD studies have shown that geometric changes like kiln height reduction, brick pattern placement can substantially increase heat transfer rates and reduce the rate of fuel consumption [28], [29]. The studies done using CFD range from detailed brick geometries to porous media representations, with turbulence models such as k–ε and k–ω SST commonly applied for efficiency [28], [30]. Radiation models, particularly the P-1 and Discrete Ordinates methods, are used to simulate high-temperature heat transfer accurately [31]. Araújo et al. performed numerical simulation using ANSYS® CFX and concluded that increasing air velocity leads to long-lasting temperature gradients on the brick surfaces and produces higher surface temperature for same exposure time [32]. Lezcano et al. studied the feasibility of replacing conventional burners with self-regenerative flameless combustion burners which achieved higher temperature of the combustion chamber that reduced the energy consumption and improved thermal efficiency [24]. These advanced studies highlight the potential of CFD in kiln research, though most studies in Nepal remain limited to manual efficiency estimation and stack monitoring, with minimal integration of simulation tools [13].

Despite these advances, most CFD studies have focused on Indian, Chinese, Mediterranean or prototype kilns and often employ idealized geometries, standard fuels, or boundary conditions that do not reflect Nepalese kiln configurations, brick-setting patterns, local fuels, and operational practices. Several studies explicitly call for validation of CFD results against field measurements because boundary conditions and fuel heterogeneity strongly affect predicted temperature uniformity and emissions [33], [34]. From the previous studies done, there is a clear gap in applying CFD in a site-specific way for Nepalese zigzag kilns with induced draft i.e. combining CFD with measured field data (fuel flow, flue gas temperatures, draft) to produce practical, validated recommendations for operators. This study addresses that gap by demonstrating the fuel and air flows, flue gas temperature, draft, kiln loading and building a CFD model calibrated with those measured boundary conditions to simulate flue-gas flow, temperature uniformity and combustion completeness across typical operating scenarios. By integrating on-site measurements validated by CFD, this study will identify the combustion optimization techniques, reducing emissions along with the possibilities of using alternative fuels in zigzag kilns operating throughout Nepal.

MATERIALS AND METHODS

This study combines field measurements, efficiency analysis, and computational simulations to evaluate energy-saving opportunities in zig-zag brick kilns and assess emission-reduction strategies.

- **Experimental Procedure**

Field data were gathered through surveys and on-site monitoring of brick kiln operations. A number of brick kilns operating inside Kathmandu Valley were visited for preliminary study and the brick stacking pattern, fuel feeding style, raw materials used for preparing green bricks etc. were studied. It was observed that most of the brick kilns operating inside the valley practiced similar patterns. The study was then carried out at H.T. Brick Factory, located at Changunarayan, Bhaktapur. Dring the experimental study, fuel consumption, firing cycles, and flue gas composition were recorded using a flue gas analyser and thermal gun. Temperature distribution along the kiln was measured to support efficiency calculations and validate simulation results. The flue gas temperature was measured using K-type thermocouples (Omega TJ36-CASS-316U, accuracy ±1.5 °C) inserted at multiple points along the flue channel. Flue gas composition (CO_2, CO, O_2) was determined using a flue gas analyzer (E Instruments E6000-5SC Handheld Gas Analyzer). Surface and ambient temperatures were measured with an infrared thermometer (Fluke 572-2 High Temperature Infrared Thermometer). Measurements were recorded over multiple firing cycles and averaged to minimize fluctuations. The overall uncertainty in temperature measurement was estimated at ±3%, and gas composition uncertainty at ±2%.

- **Efficiency Analysis**

The indirect method was employed to determine kiln efficiency by quantifying heat losses through flue gases, moisture in fuel, hydrogen combustion, openings, and surface radiation. Major losses were estimated using standard thermodynamic relations. [35].

The heat loss due to dry flue gases is given in equation (1).

$$\%\, Dry\ flue\ gas\ loss\ (L_1) = \frac{m \times c_p \times \Delta T}{GCV\ of\ fuel} \times 100\% \tag{1}$$

where, m = mass of flue gas (air + fuel), C_p = specific heat capacity, ΔT = temperature difference

Similarly, the heat loss due to evaporation of moisture present in the fuel is given in equation (2).

$$\%\, Heat\ loss\ (L_2) = \frac{M \times \{584 + C_p \times (T_{fg} - T_{amb})\}}{GCV\ of\ fuel} \times 100\% \tag{2}$$

where, M = kg of moisture present in 1 kg of fuel oil, T_{fg}= flue gas temperature, °C, T_{amb}= ambient temperature, °C, GCV = general calorific value of fuel, kCal/kg

The heat loss due to evaporation of water formed due to hydrogen is given in equation (3).

$$\%\, Heat\ loss\ (L_3) = \frac{9 \times H_2\{584 + C_p \times (T_{fg} - T_{amb})\}}{GCV\ of\ fuel} \times 100\% \tag{3}$$

where H_2= kg of H_2 in 1 kg of fuel

Similarly, the openings of the furnace are also responsible for heat loss. The heat loss due to furnace openings is given by equation (4).

$$\%\, Heat\ loss\ (L_4) = \frac{B \times A \times \propto \times\ \varepsilon}{fuel\ feeding\ rate \times GCV\ of\ fuel} \times 100\% \tag{4}$$

where B= black body radiation corresponding to temperature, A= area of the openings, $\propto$ = factor of radiation, ε= emissivity

The heat loss through furnace skin is also responsible for reducing the efficiency of the furnace. The furnace skin heat loss is given by equation (5).

$$\%\, Heat\ loss\ (L_5) = \frac{Heat\ loss\ \times Area\ of\ furnace}{fuel\ feeding\ rate \times GCV\ of\ fuel} \times 100\% \tag{5}$$

The efficiency of furnace is then calculated using indirect method by using equation (6).

$$Efficiency\ of\ furnace\ (\%) = 100 - L_1 - L_2 - L_3 - L_4 - L_5 \tag{6}$$

- **Simulation Methodology**

This study utilizes Computational Fluid Dynamics (CFD) to simulate the thermal and flow behaviour of a zig zag kiln. The objective of the simulation is to identify energy-saving opportunities by evaluating different design and operating scenarios that influence heat transfer and combustion efficiency. The simulation work draws on methodologies and boundary setups similar to those used in Alonso-Romero et al., 2024 and Refaey et al., 2021, who demonstrated the value of CFD modelling in optimizing brick kiln performance. The geometry of the kiln was recreated based on field measurements, including flue passages, air inlet zone and fuel feeding zones. The computational domain was discretized using an unstructured tetrahedral mesh with prism layers near the wall to resolve boundary layer effects. The final mesh consisted of approximately 3.7 million elements and 0.74 million nodes under the mesh size of 0.02 m. The maximum skewness was 0.84, within the acceptable limit (<0.95), ensuring reliable simulation accuracy.

To simplify the computational domain while maintaining sufficient physical accuracy, several assumptions were adopted in the CFD model. Kiln operation was modeled under steady-state conditions, reflecting the near-stable firing process during continuous operation. External heat losses through the kiln walls were neglected, as the thick brick structure and insulation layers minimize temperature gradients at the outer surfaces. The realizable k–ε turbulence model was chosen for its proven reliability in simulating recirculating and curved flow fields, which are typical in industrial furnaces [29]. Radiative heat transfer was modeled using the P-1 radiation model, offering a balance between accuracy and computational efficiency for participating media with moderate optical thickness — making it suitable for furnace-type geometries [22]. Additionally, a non-premixed combustion model with species transport was used to represent the heterogeneous solid–gas fuel interactions within the kiln. These assumptions align with methodologies adopted in previous CFD studies of industrial combustion systems.

After establishing these modeling assumptions, sensitivity and validation analyses were conducted to ensure the reliability and accuracy of the CFD model. The sensitivity analysis evaluated the effects of mesh density, turbulence, and radiation models on key thermal parameters. Model validation involved comparing simulated temperature and velocity profiles with experimental measurements obtained from the kiln. These steps were crucial to confirm grid independence, assess model robustness, and verify that numerical predictions accurately represent real kiln operating conditions.

- **Determination of excess air inside kiln combustion**

The calculation of excess air was performed to evaluate the combustion conditions of the fuels used in the kiln, namely a coal–biomass mixture (60:40 by weight) and natural gas. The analysis was based on the stoichiometric and actual air–fuel (A/F) ratios, as studies done by [29]. The stoichiometric A/F ratio ($AF_{stoichiometric}$) was first determined from the complete combustion reactions of the respective fuels:

Coal–biomass mixture (60:40): The proximate/ultimate composition of coal and biomass was used to estimate an equivalent empirical formula for the fuel blend. From this, the oxygen requirement and corresponding theoretical air demand were calculated.

Coal: $C + mH_2O + O_2 + 3.76N_2 \longrightarrow CO_2 + mH_2O(vapor) + 3.76N_2$

Biomass: $CH_{1.44}O_{0.66} + 1.03O_2 \rightarrow CO_2 + 0.72H_2O$

Natural gas: The stoichiometric combustion reaction is well-defined as:

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

which requires 2 moles of O_2 per mole of CH_4. The theoretical air demand was computed accordingly.

The actual air supply (AF_{Actual}) was obtained from the kiln's inlet air velocity measurements. The air mass flow rate was calculated using equation (7).

$$\dot{m}_{air} = \rho \times A \times v \tag{7}$$

where: ρ = air density (1.225 kg/m³ at standard conditions), A = inlet area of the duct and v = measured inlet velocity (m/s).

The air mass flow rate was then normalized to the corresponding fuel mass flow rate (coal–biomass: 0.0375 kg/s, natural gas: based on energy equivalence) to obtain the actual A/F ratio.

Finally, the percentage excess air was determined using equation (8).

$$\%\ Excess\ air = \left(\frac{AF_{actual}}{AF_{stoichiometric}} - 1\right) \times 100\% \tag{8}$$

Similarly, if $AF_{actual} < AF_{stoichiometric}$, the deficiency of air needs to be computed using equation (9).

$$\%\ Deficiency\ of\ air = \left(1 - \frac{AF_{actual}}{AF_{stoichiometric}}\right) \times 100\% \tag{9}$$

This methodology enabled quantification of the degree of excess air at different inlet velocities (4.5, 4.9, 5.4, and 6.1 m/s for coal–biomass, and 4.9 m/s for natural gas). The results were further linked with the analysis of heat loss due to flue gases, where higher excess air values directly contributed to greater sensible heat carried away by exhaust gases.

- **Emission analysis for kiln combustion**

The emission analysis due to combustion of different fuels was performed. The emissions were compared to each other under optimum operation and fuel switching scenario. Emissions for specific species and fuel types are calculated using equation (10).

$$Em_{i,j} = \sum_j Fc_j \times EF_{i,j} \tag{10}$$

where, j = Type of fuel

$Em_{i,j}$= Emission of pollutant i from fuel type j

Fc_j= Consumption of fuel type j (kg/yr)

$EF_{i,j}$ = Emission factor specific to pollutant i from fuel type j [36].

- **Cost-benefit analysis**

The cost benefit analysis was conducted by comparing the baseline scenario, in which the kiln continues to use a coal–biomass fuel mixture, and the project scenario, in which natural gas is used as the primary fuel. The framework adopts a life-cycle cost approach, incorporating capital expenditure, operating expenditure and fuel costs [37]. The incremental benefits and costs were assessed annually over the system's lifetime (typically 15 years) and discounted to present value using an appropriate discount rate. The general Net Present Value (NPV) and Benefit–Cost Ratio (BCR) were computed using the following relationships:

$$NPV = \sum_{t=0}^{T} \frac{A}{(1+r)^t} \tag{11}$$

$$BCR = \frac{B}{I + C'} \tag{12}$$

where, A, B, I and C’ denote the annuity, annual benefits, investment and present value of annual operation costs at time t, r is the discount rate, and t is the project lifetime [38]. The Internal Rate of Return (IRR) was also determined as the discount rate at which NPV equals zero.

RESULTS AND DISCUSION

The outcomes of field measurements, efficiency analysis, and CFD simulations, highlighting their interrelation in evaluating kiln performance. It further interprets the findings in comparison with experimental data and relevant literature to identify key energy-saving and emission-reduction opportunities.

A. Furnace Performance

The comparison of the furnace performance was done from both the experimental data and the data obtained from the simulation. The efficiency of the brick kiln using indirect method was found to be 52.63%. The indirect method for efficiency calculation of the brick kiln indicated that flue gas (31.62%), furnace openings (9.28%) and furnace surface (2.89%) are the major areas for energy loss. These losses align with previous studies performed in brick kilns [23]. To minimize the inefficiency, the loss from these areas must be minimized. The major causes of energy loss in each section are:

Flue gas: Flue gas is the gas exiting to the atmosphere via a flue, which is a pipe or channel for conveying exhaust gases from combustion, as from a fireplace, oven, furnace, boiler or steam generator. Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost. The higher the temperature of flue gas, the higher would be the losses from the flue gases. For every temperature decrease of 22°C from the flue gas, the fuel consumption would be reduced by 1% [35]. The loss from the furnace could be minimized if the flue gas can be utilized for air preheating.

Furnace openings: The furnace has openings on various places for the input of fuels for combustion. The heat obtained from the combustion of the fuel would be utilized for drying the bricks. The larger the openings, the higher would be the heat loss that would lead to inefficiency of the kiln.

Furnace surface: The walls and roof of the furnace may not be properly insulated. Hence a large amount of heat loss will be from these areas. The roof, walls and surface of the kiln could be properly insulated to reduce the heat loss from the furnace which can improve the thermal efficiency of the kiln.

B. CFD Simulation

The CFD model was solved using defined boundary conditions for both coal–biomass and natural gas. Inlet air velocity ranged from 4.5–6.1 m/s for coal–biomass and was fixed at 4.9 m/s for natural gas, with corresponding fuel mass flow rates of 0.0375 kg/s and 0.017 kg/s. The system was assumed adiabatic to neglect external heat losses, and simulations were carried out under steady-state conditions. A coupled pressure–velocity solver was used to capture the strong interaction between flow and combustion, while outlet pressure was fixed at 1 bar to represent atmospheric discharge through the chimney.

- Coal-biomass firing: This mixture of fuel demonstrated localized hot spots, uneven heating, and incomplete combustion at low air velocities.
- Natural gas firing: Using natural gas produced uniform temperature distribution, steady-state conditions, and higher combustion efficiency.

The temperature profile of brick stacks at an air velocity of 4.5 m/s, the is the lowest among all conditions, ranging between 800 – 850 °C. The low velocity results in poor turbulence, reduced mixing of fuel and oxidizer, and consequently, incomplete combustion. This condition fails to provide adequate thermal energy for efficient brick firing, which could compromise product quality and prolong the firing cycle. When the air velocity is increased to 4.9 m/s, the temperature distribution improves substantially, ranging from 950 – 990 °C. At an air inlet velocity of 5.4 m/s, the temperature rises significantly, ranging from approximately 1030 °C at the kiln inlet to 1060 °C at the end of the brick stack. The temperature also falls under optimum firing range for green bricks. The enhanced turbulence promotes better air–fuel mixing, ensuring more complete combustion. The highest velocity case, 6.1 m/s, produces the maximum temperature profile, beginning at about 1240 °C and increasing to nearly 1270 °C. This steep increase indicates highly effective mixing and efficient fuel oxidation due to increased turbulence intensity. Such a condition maximizes thermal energy release but may risk localized overheating and higher thermal gradients. Excessively high firing temperatures can lead to issues such as brick warping, microcracking, and increased thermal stress on the kiln walls.

The simulation was performed using natural gas at an air velocity of 4.9 m/s which produced a more uniform temperature profile, with faster attainment of steady-state conditions and fewer cold spots. The distribution shows relatively uniform heating throughout the firing channels, with peak temperatures localized in the central combustion zones. The temperature distribution profile of the brick kilns under different air-fuel condition inside the brick kiln are represented from Figure 1 to Figure 5.

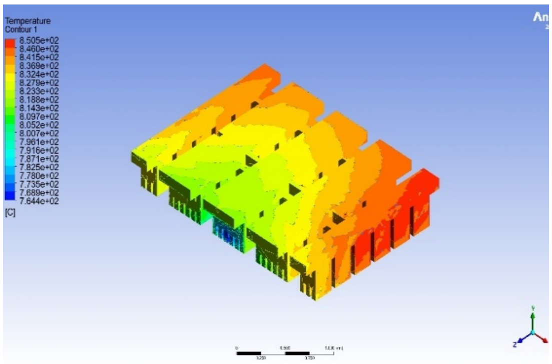

Figure 1: Temperature contours of the brick stack using coal-biomass mixture at an air velocity of 4.5 m/s

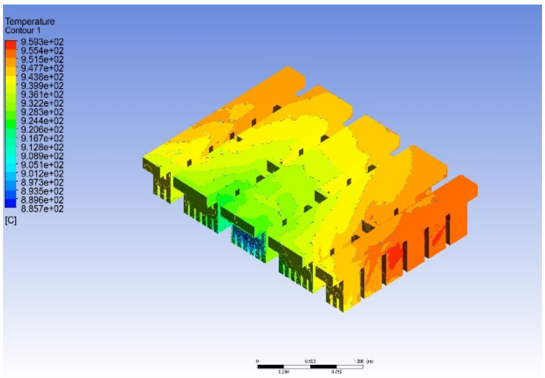

Figure 2: Temperature contours of the brick stack using coal-biomass mixture at an air velocity of 4.9 m/s

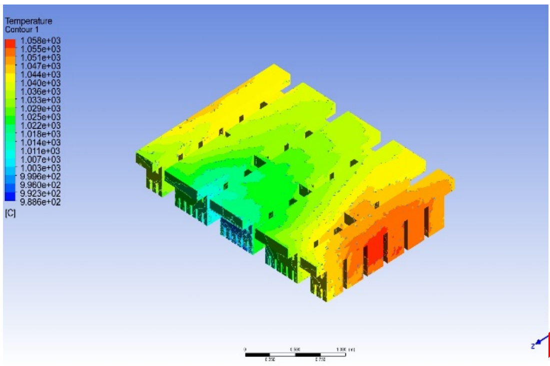

Figure 3: Temperature contours of the brick stack using coal-biomass mixture at an air velocity of 5.4 m/s

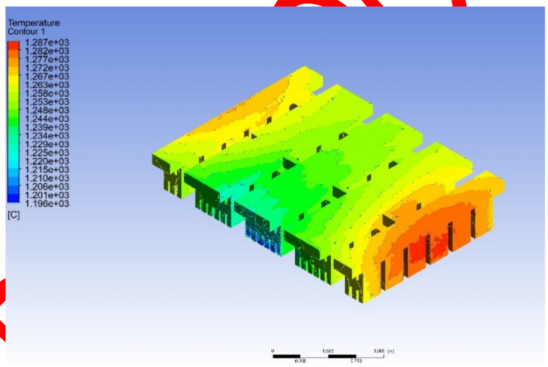

Figure 4: Temperature contours of the brick stack using coal-biomass mixture at an air velocity of 6.1 m/s

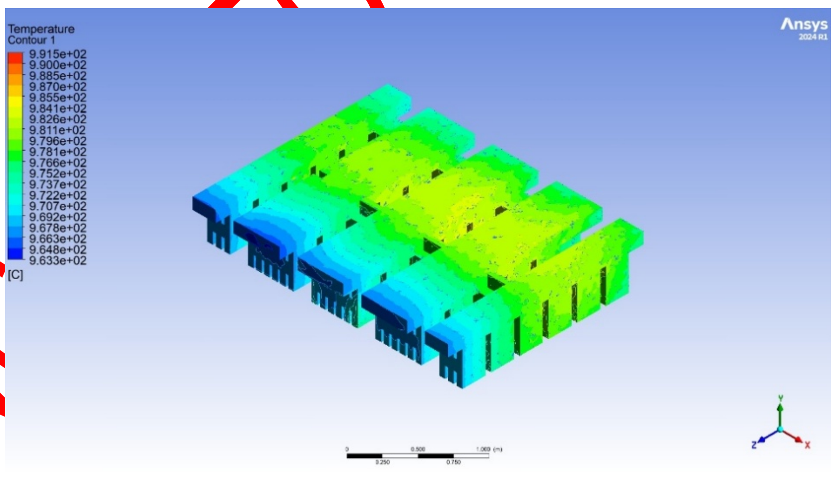

Figure 5: Temperature contours of the brick stack for natural gas combustion at an air velocity of 4.9 m/s

The temperature of length of brick stacks in z-direction under the fuel input of coal-biomass mixture at the air inlet velocity of 4.9 m/s and at an air inlet velocity of 5.4 m/s were found to be under optimum condition as the temperature of the stack lies between 900 °C to 1050 °C. Similarly, natural gas was also employed as a fuel at an air inlet velocity of 4.9 m/s i.e. under optimum conditions. The temperature of the uppermost part of the brick stack along z-direction under the optimum conditions are given in Figure 6. These results highlight the advantage of natural gas substitution, which not only ensures more controlled combustion but also contributes to reduced pollutant emissions, improved kiln efficiency, and better-quality firing outcomes.

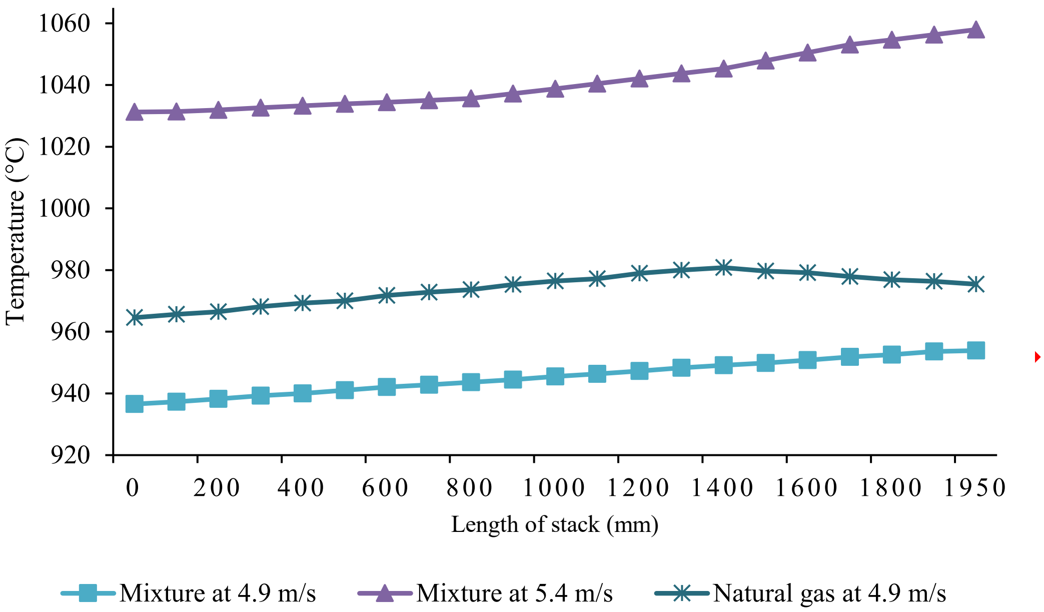

Figure 6: Temperature distribution along the brick stacking

C. Energy and Emission Performance

For the coal–biomass mixture, the flue gas losses vary considerably with inlet air velocity. At 4.5 m/s, the loss is 14.05%, increasing to 15.58% at 4.9 m/s and reaching the highest value of 20.16% at 6.1 m/s. This rise in flue gas losses directly reduces the overall efficiency, which drops from over 70% at lower velocities to just 64.09% at the highest velocity. Among the tested conditions, the kiln operates well at the velocity ranging from 4.9-5.4 m/s, as the flue gas loss of 14.49% to 15.58% ensures the stack temperature is maintained at an optimal level without excessively compromising the final efficiency (68.67% - 69.76%). This makes it the most balanced operating condition for solid fuel combustion in the kiln. When natural gas is used, flue gas losses are significantly lower, recorded at only 3.86% under the same 4.9 m/s condition. This minimal loss translates into a much higher final efficiency of 80.39%. A comparative graph between the change of flue gas loss to the overall efficiency of the furnace is given in Figure 7.

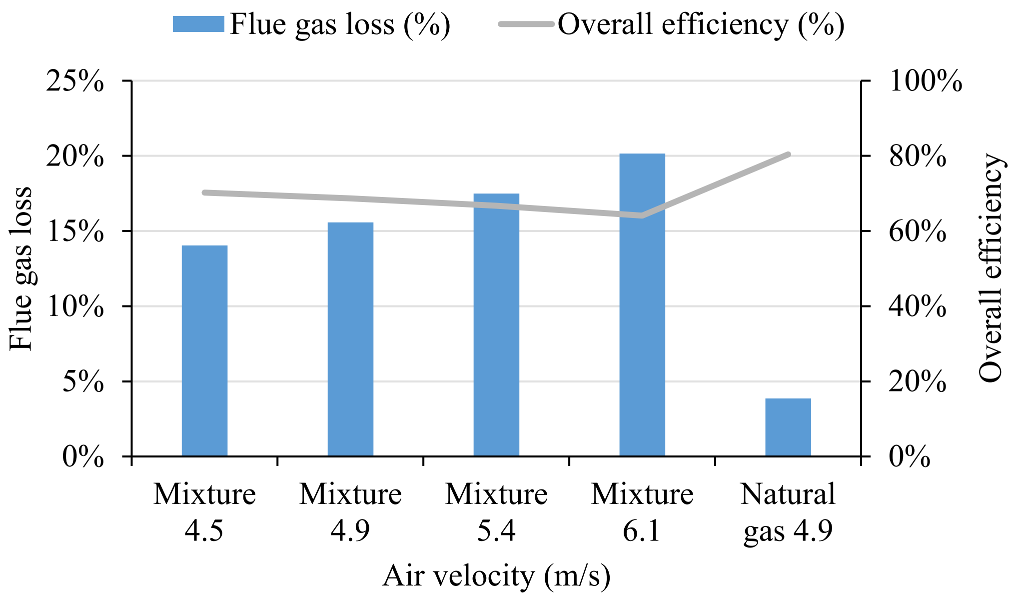

Figure 7: Comparison of overall efficiency under different conditions

The combined field data and CFD simulation results reveal clear contrasts between coal–biomass and natural gas operation modes, while also highlighting critical operating parameters that influence efficiency and emissions. The temperature and velocity distributions inside the kiln exhibit nonuniformity due to flow recirculation and heat stratification, particularly near wall boundaries and corners. Such conclusion have been drawn from previous studies done by Ngom et al. where flow stagnation and localized hotspots reduce thermal uniformity [39].

When comparing fuels, the coal-biomass mixture shows larger sensible heat losses through the flue gases than natural gas, reinforcing that solid fuels inherently carry away more enthalpy as exhaust. Yet, by fixing the stack velocity at the range of 4.9 - 5.4 m/s for the coal–biomass case, the kiln avoids the steep increase in flue-gas heat loss seen at higher velocities while maintaining robust combustion. Alonso-Romero et al. has also demonstrated the changes in thermal efficiency using transient kiln analysis under different air-fuel ratio, which emphasize the trade-off between excess air and thermal efficiency [30].

Energy output and emissions comparisons further underscore the environmental advantage of gaseous fuel operation. The coal–biomass mixture delivers 5.63 TJ of energy whereas 6.23 TJ energy is delivered from natural gas. Coal-biomass mixture yet emits 496.39 tonnes of CO_2 compared with 349.62 tonnes from natural gas a nearly 30% CO_2 reduction for equivalent output. Natural gas emissions intensify this difference (0.10 tonnes vs. 0.01 tonnes), owing to methane's high global warming potential. In CO_2-equivalent terms, the coal–biomass footprint is markedly higher. Locally, coal–biomass emits 0.01 tonnes PM_{10} while almost neglectable PM_{10} emission was observed in case of natural gas. Similarly, more CO (4.44 tonnes vs. 12.46 tonnes) was found the latter likely due to incomplete combustion under suboptimal air mixing, a challenge also noted in review studies of brick kiln emissions [40].

These results align with broader literature that finds fuel choice, airflow control, and kiln design to be pivotal in both energy efficiency and pollution mitigations like brick kiln emission reviews [40], CFD kiln studies [26]. In practice, these findings suggest that retrofitting or operational tuning like inlet air velocity optimization, airflow distribution arrangement may yield large gains even before full fuel transition. The natural gas scenario most clearly demonstrates how improved combustion control can decouple high thermal output from high emissions.

D. Economic Feasibility for Natural Gas Substitution

This cost–benefit analysis was carried out to evaluate the economic feasibility of substituting the existing 60:40 coal–biomass fuel mixture with natural gas in the case study brick kiln. The assessment was based on a 15-year project lifetime with a discount rate of 8%, in line with similar techno-economic studies conducted for cleaner fuel transitions in brick industries [37].

The required fuel energy input was determined using the relationship between useful energy demand and thermal efficiency ($Q_{in}=Q_u/\eta$). For the coal–biomass mixture, the annual input energy was found to be 8,042.85 GJ/year, whereas for natural gas, it was reduced to 7,787.5 GJ/year due to its higher combustion efficiency. The annual fuel cost for the existing coal–biomass system was NPR 7.75 million, while the equivalent cost for natural gas was NPR 7.01 million. Including operation and maintenance expenses, the total annual operating costs were NPR 9.75 million and NPR 8.21 million for the coal–biomass and natural gas systems, respectively. This indicates an annual cost saving of NPR 1.54 million following fuel substitution.

To evaluate investment attractiveness, key economic indicators were computed. The Net Present Value (NPV) was found to be NPR 9.15 million, the Benefit–Cost Ratio (BCR) was 3.28, the Internal Rate of Return (IRR) was approximately 30.8%, and the simple payback period was 2.6 years. These values indicate that the transition to natural gas is financially viable, with high returns and short payback duration.

Furthermore, the substitution contributes to environmental improvement by eliminating solid fuel handling, reducing particulate matter, and cutting CO_2 and SO_2 emissions consistent with findings from recent studies that report up to 40–60% emission reduction when brick kilns transition from solid to gaseous fuels [37]. Overall, the results confirm that adopting natural gas not only provides substantial economic savings but also yields significant environmental benefits, thereby supporting a cleaner and more sustainable production pathway for Nepal's brick industry.

CONCLUSION

This study evaluated the performance, efficiency, and feasibility of substituting the existing 60:40 coal–biomass mixture with natural gas in a zigzag brick kiln through experimental analysis, CFD simulation, and economic assessment. The results identified the optimum air velocity range of 4.9–5.4 m/s at a fuel feeding rate of 0.0375 kg/s as the most stable and energy-efficient operating condition for coal-biomass mixture. Similarly, the optimum velocity of 4.9 m/s at a fuel feeding rate of 0.017 kg/s achieved eve better condition for natural gas. Under these conditions, the coal–biomass system achieved thermal efficiencies between 68.7–69.8% with flue gas losses of 14.5–15.6%, while the natural gas system attained an efficiency of 80.4% with only 3.86% flue gas loss. The temperature distribution within this range i.e. 940 °C – 1,050°C for coal–biomass mixture and 960 °C – 1,080 °C for natural gas, ensured uniform firing and improved brick quality.

The environmental and economic outcomes of fuel substitution were equally significant. The annual CO_2 emissions decreased by 29.6%, SO_2 emissions by 95%, and particulate matter emissions were nearly eliminated. The shift also reduced the annual operating cost from NPR 9.75 million to NPR 8.21 million, generating an annual saving of NPR 1.54 million, with an NPV of NPR 9.15 million, BCR of 3.28, IRR of 30.8%, and a payback period of 2.6 years, confirming the financial viability of natural gas adoption. Overall, natural gas offers superior energy efficiency, lower emissions, and higher economic returns compared to the coal–biomass mixture, supporting Nepal's industrial decarbonization goals.

ACKNOWLEDGEMENT(S)

The authors would like to acknowledge the University Grants Commission, Sanothimi, Bhaktapur, Nepal for granting us with UGC Faculty Research Grant (FRG-81/82-Engg-02).

References

[1] P. Baral, A. Eil, J. Li, and E. Saikawa, 'DIRTY STACKS, HIGH STAKES: An Overview of Brick Sector in South Asia', The World Bank, 2020. Accessed: Aug. 17, 2025. [Online]. Available: http://documents.worldbank.org/curated/en/685751588227715919

[2] ICIMOD, 'Brick sector in Nepal - Fact Sheet', International Centre for Integrated Mountain Development (ICIMOD), 2019. Accessed: Aug. 17, 2025. [Online]. Available: https://lib.icimod.org/records/1t4jt-maf42

[3] S. Thakuri, A. Basnet, K. Rawal, R. Chauhan, R. Manandhar, and P. Y. Rai, 'Technologies, emission estimation, and feasibility of cleaner technologies in brick industry of Nepal', *Environmental Challenges*, vol. 15, p. 100928, Apr. 2024, doi: 10.1016/j.envc.2024.100928.

[4] N. Brooks *et al.*, 'Reducing emissions and air pollution from informal brick kilns: Evidence from Bangladesh', *Science*, vol. 388, no. 6747, p. eadr7394, May 2025, doi: 10.1126/science.adr7394.

[5] S. Nepal *et al.*, 'A Comparative Study of Stack Emissions from Straight-Line and Zigzag Brick Kilns in Nepal', *Atmosphere*, vol. 10, no. 3, p. 107, Mar. 2019, doi: 10.3390/atmos10030107.

[6] Sameer Maithel, 'Evaluating Energy Conservation Potential of Brick Production in India', SAARC Energy Centre, Islamabad, 2013. Accessed: Aug. 21, 2025. [Online]. Available: https://www.saarcenergy.org/wp-content/uploads/2022/06/2012-Final-Report-Evaluating-Energy-Conservation-in-Brick-Production-in-India.pdf

[7] Y. P. Chapagain, S. Sapkota, D. B. Ghale, N. B. Bohara, N. Duwal, and J. Bhattarai, 'A case study on mineralogy and physico-mechanical properties of commercial bricks produced in Nepal', *SN Appl. Sci.*, vol. 2, no. 11, p. 1856, Nov. 2020, doi: 10.1007/s42452-020-03535-y.

[8] N. Bohara, D. Ghale, Y. Chapagain, N. Duwal, and J. Bhattarai, 'Effect of firing temperature on physico-mechanical properties of contemporary clay brick productions in Lalitpur, Nepal', *Bangladesh J. Sci. Ind. Res.*, vol. 55, no. 1, pp. 43–52, Apr. 2020, doi: 10.3329/bjsir.v55i1.46731.

[9] E. Tsega, A. Mosisa, and F. Fufa, 'Effects of Firing Time and Temperature on Physical Properties of Fired Clay Bricks', *AJCE*, vol. 5, no. 1, p. 21, 2017, doi: 10.11648/j.ajce.20170501.14.

[10] N. B. Bohara, L. B. Bhat, D. B. Ghale, N. Duwal, and J. Bhattarai, 'Investigation of the firing temperature effects on clay brick sample; Part-I: Mineralogical phase characterization', *BIBECHANA*, vol. 16, pp. 122–130, Nov. 2018, doi: 10.3126/bibechana.v16i0.21319.

[11] U. Rajarathnam *et al.*, 'Assessment of air pollutant emissions from brick kilns', *Atmospheric Environment*, vol. 98, pp. 549–553, Dec. 2014, doi: 10.1016/j.atmosenv.2014.08.075.
[12] Y. Chen *et al.*, 'Stack and fugitive emissions of major air pollutants from typical brick kilns in China', *Environmental Pollution*, vol. 224, pp. 421–429, May 2017, doi: 10.1016/j.envpol.2017.02.022.
[13] D. P. Sah, A. K. Mishra, R. Shakya, and P. K. Sah, 'Status of Brick Kilns Stack Emission in Kathmandu Valley of Nepal', *JoARCEE*, vol. 06, no. 3 & 4, pp. 1–9, Jan. 2020, doi: 10.24321/2393.8307.201906.
[14] S. A. Hussnain *et al.*, 'Thermal Analysis and Energy Efficiency Improvements in Tunnel Kiln for Sustainable Environment', *Processes*, vol. 9, no. 9, p. 1629, Sept. 2021, doi: 10.3390/pr9091629.
[15] H. Valdes, J. Vilches, G. Felmer, M. Hurtado, and J. Figueroa, 'Artisan Brick Kilns: State-of-the-Art and Future Trends', *Sustainability*, vol. 12, no. 18, p. 7724, Sept. 2020, doi: 10.3390/su12187724.
[16] A. Bouchahma, A. Malaki, R. Moussaoui, M. Cherraj, and D. El Hachmi, 'Study of thermal transition in brick kilns: modeling wood consumption and energy efficiency', *Multidiscip. Sci. J.*, vol. 7, no. 7, p. 2025309, Dec. 2024, doi: 10.31893/multiscience.2025309.
[17] R.-H. Chavez, 'Energy analysis of two coupled brick kilns: an experimental study', *Clean Techn Environ Policy*, vol. 23, no. 8, pp. 2235–2249, Oct. 2021, doi: 10.1007/s10098-021-02130-y.
[18] S. Ahmed *et al.*, 'Improving the Thermal Performance and Energy Efficiency of Buildings by Incorporating Biomass Waste into Clay Bricks', *Materials*, vol. 16, no. 7, p. 2893, Apr. 2023, doi: 10.3390/ma16072893.
[19] J. K. Arora, P. Singh, K. Garg, M. Singh, A. Aggarwal, and S. Bala, 'Partial replacement of coal with paddy straw pellets as fuel in brick kilns', *Biomass Conv. Bioref.*, vol. 15, no. 8, pp. 12713–12726, Apr. 2025, doi: 10.1007/s13399-024-06064-5.
[20] K. F. Biswas, B. M. Ghauri, and L. Husain, 'Gaseous and aerosol pollutants during fog and clear episodes in South Asian urban atmosphere', *Atmospheric Environment*, vol. 42, no. 33, pp. 7775–7785, Oct. 2008, doi: 10.1016/j.atmosenv.2008.04.056.
[21] M. W. Khan, Y. Ali, F. De Felice, A. Salman, and A. Petrillo, 'Impact of brick kilns industry on environment and human health in Pakistan', *Science of The Total Environment*, vol. 678, pp. 383–389, Aug. 2019, doi: 10.1016/j.scitotenv.2019.04.369.
[22] F. Tasnim, F. Istiaque, A. M. Morshed, and M. U. Ahmad, 'A CFD investigation of conventional brick kilns', presented at the 8TH BSME INTERNATIONAL CONFERENCE ON THERMAL ENGINEERING, Dhaka, Bangladesh, 2019, p. 040006. doi: 10.1063/1.5115877.
[23] J. A. Lara-Mireles, R. Zitzumbo-Guzmán, J. E. Frías-Chimal, J. M. López-Vela, and S. Alonso-Romero, 'Experimental and numerical analysis of the artisanal brick-burning process in an MK2 Kiln', *J. King Saud Univ. – Eng. Sci.*, vol. 37, no. 5, p. 20, Aug. 2025, doi: 10.1007/s44444-025-00032-8.
[24] C. Lezcano, C. Echeverri-Uribe, Y. López, and A. Amell, 'Numerical simulation of a batch furnace for heating of ceramic bricks using flameless combustion burners', *Case Studies in Thermal Engineering*, vol. 76, p. 107266, Dec. 2025, doi: 10.1016/j.csite.2025.107266.
[25] M. Milani, L. Montorsi, M. Stefani, R. Saponelli, and M. Lizzano, 'Numerical analysis of an entire ceramic kiln under actual operating conditions for the energy efficiency improvement', *Journal of Environmental Management*, vol. 203, pp. 1026–1037, Dec. 2017, doi: 10.1016/j.jenvman.2017.03.076.

[26] A. Beyene, V. Ramayya, and G. Shunki, 'CFD Simulation of Biogas Fired Clay Brick Kiln', *American Journal of Engineering and Applied Sciences*, vol. 11, no. 2, pp. 1045–1061, Feb. 2018, doi: 10.3844/ajeassp.2018.1045.1061.
[27] I. F. Almesri, M. A. Alrahmani, J. H. Almutairi, and H. Z. Abou-Ziyan, 'Correlations of Heat Transfer and Fluid Flow Data for Lattice Brick Settings in Tunnel Kilns', *Energies*, vol. 16, no. 9, p. 3631, Apr. 2023, doi: 10.3390/en16093631.
[28] H. A. Refaey, M. A. Alharthi, M. R. Salem, A. A. Abdel-Aziz, H. E. Abdelrahman, and M. A. Karali, 'Numerical investigations of convective heat transfer for lattice settings in brick tunnel Kiln: CFD simulation with experimental validation', *Thermal Science and Engineering Progress*, vol. 24, p. 100934, Aug. 2021, doi: 10.1016/j.tsep.2021.100934.
[29] S. Alonso-Romero, J. A. Alfaro-Ayala, J. E. Frias-Chimal, O. A. López-Núñez, J. D. J. Ramírez-Minguela, and R. Zitzumbo-Guzmán, 'A Transient Combustion Study in a Brick Kiln Using Natural Gas as Fuel by Means of CFD', *Processes*, vol. 13, no. 8, p. 2437, Aug. 2025, doi: 10.3390/pr13082437.
[30] S. Alonso-Romero, J. A. Alfaro-Ayala, J. E. Frias-Chimal, J. J. Ramírez-Minguela, and O. A. López-Núñez, 'Transient thermal analysis of a kiln using different numerical approaches by means of CFD', *Case Studies in Thermal Engineering*, vol. 64, p. 105441, Dec. 2024, doi: 10.1016/j.csite.2024.105441.
[31] C. Cintolesi, H. Nilsson, A. Petronio, and V. Armenio, 'Numerical simulation of conjugate heat transfer and surface radiative heat transfer using the P 1 thermal radiation model: Parametric study in benchmark cases.', *International Journal of Heat and Mass Transfer*, vol. 107, pp. 956–971, Apr. 2017, doi: 10.1016/j.ijheatmasstransfer.2016.11.006.
[32] M. V. Araújo, J. M. P. Q. Delgado, and A. G. Barbosa De Lima, 'On the Use of CFD in Thermal Analysis of Industrial Hollow Ceramic Brick', *DF*, vol. 10, pp. 70–82, June 2017, doi: 10.4028/www.scientific.net/DF.10.70.
[33] J. Unterluggauer, M. Schieder, S. Gutschka, S. Puskas, S. Vogt, and B. Streibl, 'Numerical Investigations on the Enhancement of Convective Heat Transfer in Fast-Firing Brick Kilns', *Energies*, vol. 17, no. 22, p. 5617, Nov. 2024, doi: 10.3390/en17225617.
[34] H. A. Refaey *et al.*, 'Fluid Flow Characteristics for Four Lattice Settings in Brick Tunnel Kiln: CFD Simulations', *Buildings*, vol. 13, no. 3, p. 733, Mar. 2023, doi: 10.3390/buildings13030733.
[35] Bureau of Energy Efficiency, 'Energy Performance Assessment of Furnaces', Bureau of Energy Efficiency, New Delhi. Accessed: Aug. 21, 2025. [Online]. Available: https://www.beeindia.gov.in/sites/default/files/4Ch2.pdf
[36] Ram M. Shrestha *et al.*, 'Atmospheric Brown Clouds (ABC) Emission Inventory Manual', United Nations Environment Programme, Nairobi, Kenya, 2013.
[37] G. R. Timilsina, S. Malla, and M. P. Heger, 'Economic and Policy Analysis of Clean Technologies for Brick Production in Nepal', 2025, *SSRN*. doi: 10.2139/ssrn.5133624.
[38] Chan S. Park, *Contemporary engineering economics*, 4th ed. Upper Saddle River, N.J.: Prentice Hall, 2007.
[39] M. Ngom, A. Thiam, A. Balhamri, V. Sambou, T. Raffak, and H. A. Refaey, 'Transient study during clay bricks cooking in the traditional kiln; CFD numerical study', *Case Studies in Thermal Engineering*, vol. 28, p. 101672, Dec. 2021, doi: 10.1016/j.csite.2021.101672.
[40] M. S. Bhat, Q. S. Afeefa, K. P. Ashok, and A. G. Bashir, 'Brick kiln emissions and its environmental impact: A Review', *J. Ecol. Nat. Environ.*, vol. 6, no. 1, pp. 1–11, Jan. 2014, doi: 10.5897/JENE2013.0423.