

DEVELOPMENT AND PERFORMANCE ASSESSMENT OF A DUAL-ENERGY SOURCE BAKING OVEN FOR DOMESTIC AND SMALL-SCALE INDUSTRIAL APPLICATIONS

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Abstract

This study presents the design, fabrication, and performance evaluation of a dual-energy baking oven powered by charcoal and liquefied petroleum gas (LPG). The oven was developed to address persistent challenges in traditional baking systems, particularly those related to energy accessibility, operational cost, and thermal efficiency. Its application is intended for both domestic households and small-scale industrial settings. Performance assessment was conducted based on critical parameters such as heating rate, maximum temperature, temperature uniformity, thermal efficiency, fuel consumption, and the quality of baked products. Experimental findings indicate that the LPG mode achieved the target baking temperature of 180 °C within 9 minutes, whereas charcoal required 16 minutes to reach the same level. Despite the difference in heating rate, both energy sources were capable of attaining a maximum temperature of 250 °C. However, LPG exhibited superior temperature stability (± 10 °C) compared to charcoal (± 18 °C). Thermal efficiency was measured at 31.5% for LPG and 22.3% for charcoal, while fuel consumption was 0.38 kg/hr and 0.90 kg/hr, respectively. Practical baking tests using meat pie and grilled fish demonstrated that the LPG-powered oven provided more uniform cooking, better heat control, and faster operation, whereas the charcoal-powered mode produced a traditional smoky flavour but with less consistency. The findings demonstrate that the dual-energy configuration provides operational flexibility, enabling users to alternate between fuels according to their availability and cost-effectiveness. This adaptability enhances the oven's practicality across diverse contexts, making it suitable for households, street vendors, and small-scale bakeries. Overall, the system offers a cost-efficient and energy-resilient solution that can significantly improve food processing, particularly in low-income and off-grid communities.

Keywords: Baking performance; Charcoal; Dual-fuel baking oven; Liquefied Petroleum Gas (LPG); Small-scale food processing; Thermal efficiency

How to Cite: Adeduntan A. S.; Adejumobi A. O.; Oladiji A. O.; Morakinyo T. O.; Rasaq U. A. and Ajao L. A. (2025). Development and performance assessment of a dual-energy source baking oven for domestic and small-scale industrial applications. *OYSCATECH Journal of Engineering and Environmental Studies*, 3(1), 51-60. <https://oyscatechpublications.org/>

Introduction

In many developing countries, including Nigeria, the food processing sector—particularly baking—depends heavily on thermal energy derived from fossil fuels and biomass. Baking ovens are central to the production of staple foods such as bread, pastries, and snacks, serving both domestic households and small-scale industrial markets. However, reliance on single-source energy systems such as electricity or firewood has posed significant challenges, including unstable energy supply, high operational costs, and negative environmental consequences (Oladeji, 2019; FAO, 2020). In response to these limitations, growing attention has been directed toward the development of dual-energy ovens designed to enhance energy availability, improve flexibility in fuel use, and support sustainability goals.

Charcoal and liquefied petroleum gas (LPG) are two energy sources that are widely accessible across rural and urban communities in sub-Saharan Africa. Charcoal remains relatively affordable and is readily obtainable, particularly in off-grid regions, whereas LPG is associated with cleaner combustion and higher energy density (Omodara *et al.*, 2020). Integrating these fuels in a dual-source oven provides users with a practical solution for building energy redundancy, reducing dependence on a single fuel source, and mitigating the risks of fluctuating prices and supply chain disruptions. Such systems can strengthen the operational reliability of baking ovens in contexts where energy infrastructure is often weak or inconsistent.

Moreover, the integration of charcoal and LPG addresses several Sustainable Development Goals (SDGs), including SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), and SDG 12

(responsible consumption and production) (United Nations, 2015). It contributes to cleaner cooking technologies by reducing emissions compared to traditional wood-fired ovens and enhancing thermal efficiency, thus promoting resource conservation and productivity (Kareem *et al.*, 2022).

While several studies have been conducted on single-fuel ovens (especially LPG, or biomass-fired models), in some detail, not much research has been carried out on hybrid ovens that are fired with charcoal and LPG. Previous studies have focused more on LPG-electric or solar-electric hybrid ovens (Aremu *et al.*, 2021; Odesola *et al.*, 2021) with little consideration of solid-liquid fuel combinations feasible in low-income or energy-deprived settings.

The design, fabrication and testing of the dual-energy operated charcoal and LPG fired baking oven is reported in this study. The specific objective is to develop and construct a low-cost oven system using locally available materials and evaluate the ovens performance regarding thermal efficiency, baking duration, fuel usage and heat distribution. The oven was broadly evaluated regarding its potential for domestic use or small-scale industrial use with regard to potential energy constrained conditions.

Materials and Method

Choosing the right materials for the baking oven was crucial in order to guarantee the device's functionality, safety and cost effectiveness, particularly when used in either a domestic or small-scale commercial setting. This choice of materials was influenced by the thermal properties, mechanical strength, resistance to corrosion and availability of materials at local market prices (Aremu *et al.* 2021; Oladeji 2019).

Table 1. Components, selection of materials and justification for their selection

S/N	Component	Material	Justification
1	Oven body	Mild steel (1.5 mm)	Structural strength, machinability
2	Baking chamber lining	Galvanized steel	Corrosion-resistant, food-safe
3	Insulation	fibre wool (25 mm thick)	Low thermal conductivity, 1050°C resistance
4	Charcoal grate	Cast iron	High-temperature strength
5	LPG piping	Copper tubing + brass nozzle	High thermal conductivity, leak resistance
6	Thermometer/sensor	Glass	Availability
7	Burner	Dual-ring stainless steel	Efficient flame distribution

2.1 Design Considerations

The dual-powered baking oven was thoughtfully designed to run on either charcoal or LPG, offering users flexibility in fuel choice. This makes it especially suitable for rural and semi-urban areas where energy access can be inconsistent. The design focused on reducing heat loss, promoting even heat distribution, and improving fuel efficiency—all while using readily available local

materials. To ensure practical performance, the oven was built to reach internal temperatures between 150 and 250 °C. It features a baking chamber of around 50 litres, making it ideal for both household use and small-scale businesses. Additionally, it was engineered to achieve a minimum thermal efficiency of 20%, as verified through standard water boiling tests.

Table 2. Component parts of the oven

S/N	Component	Quantity
1	Baking tray	3
2	Gas regulator	1
3	Frame	1
4	Temperature gauge	1
5	Burner	1
6	Perforated plate	1
7	Oven door	1
8	Hinges	2
9	Slot lock	1
10	Oven firing door	1
11	Chimney	1

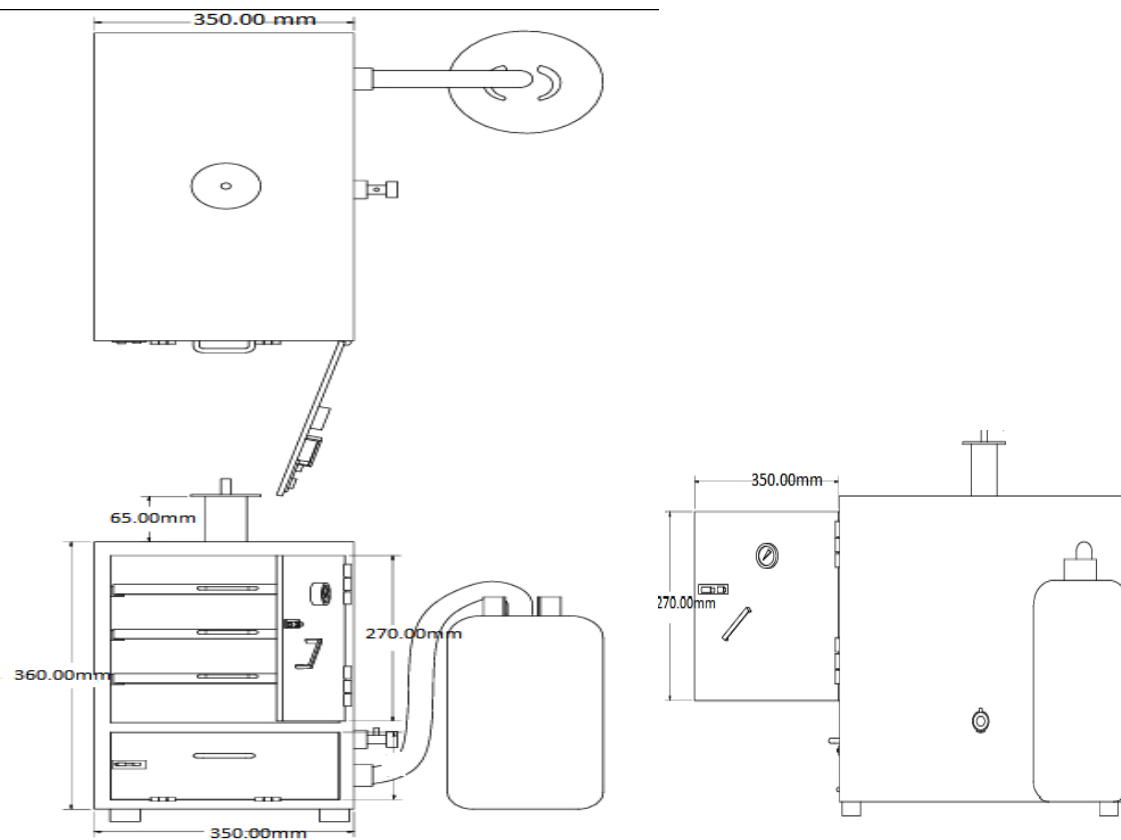


Figure. 1. Orthographic diagram showing the proposed dual-energy source baking oven

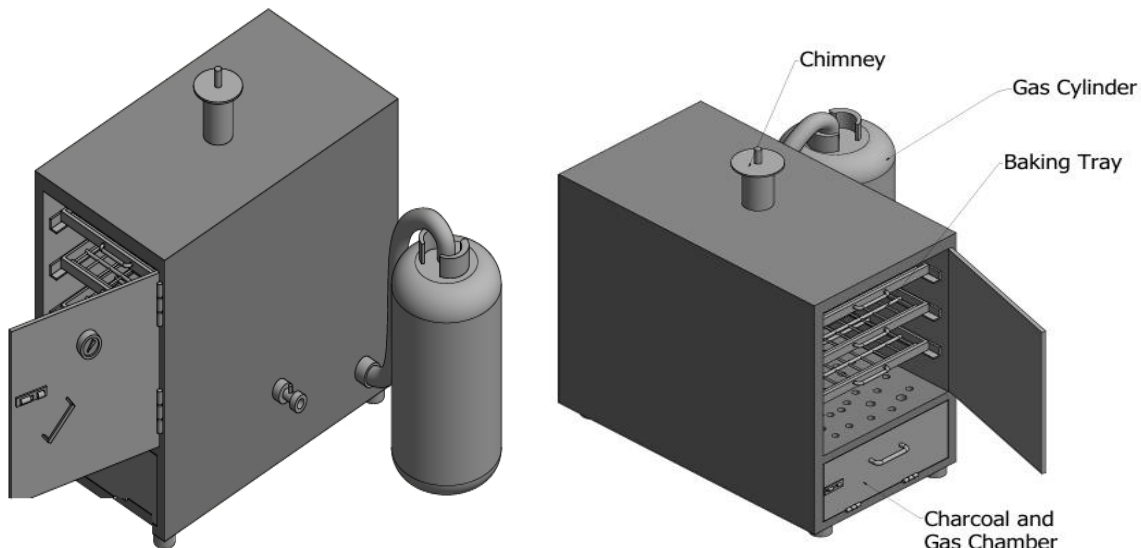


Figure. 2. 3D diagram showing the proposed dual-energy source baking oven

2.1.1 Oven Chamber Design and Sizing

The oven was designed with a rectangular box-like (cuboidal) geometry. The internal volume (V) was calculated based on a desired chamber capacity of 50 L:

$$V = L \times W \times H$$

$$= 400mm \times 350mm$$

$$\times 360mm = 504mm^3$$

$$\approx 50.4L$$

This sizing allows for 3 baking trays, with a vertical clearance for airflow and convection circulation.

2.1.2 Heat Energy Requirement

Heat Required to Raise Air Temperature

The amount of heat energy (Q) required to raise the temperature of air and the baking mass inside the oven from ambient (30°C) to the target baking temperature (200°C) was estimated using: $Q = m \times C_p \times \Delta T$

Where:

$$m = \text{mass of air in the chamber} = \rho \cdot V$$

$$\rho = 1.2 \text{ kg/m}^3 (\text{density of air}), \quad V = 0.0504 \text{ m}^3$$

$$C_p = \text{specific heat capacity of air} = 1005 \text{ J/kg.K}$$

$$\Delta T = \text{Temperature rise} = 200^\circ\text{C} - 30^\circ\text{C} = 170$$

$$m = 1.2 \times 0.0504 = 0.0605 \text{ kg}$$

$$Q = 0.0605 \times 1005 \times 170 = 10,337.2 \text{ J} \approx 10.3 \text{ kJ}$$

Heat Required to Raise Temperature of Food Mass

Assume:

$$\text{Mass of food} = m_{\text{food}} = 0.15 \text{ kg}$$

$$\text{Specific heat of food} = C_p = 2720 \text{ J/kg.K} (\text{typical for bread dough or similar})$$

$$\text{Temperature rise} = \Delta T = 200^\circ\text{C} - 30^\circ\text{C} = 170^\circ\text{C}$$

$$Q_{\text{food}} = 0.15 \times 2720 \times 170 = 69,360 \text{ J} \approx 69.4 \text{ kJ}$$

Total Useful Heat Required (Air + Food):

$$Q_{\text{Useful}} = Q_{\text{air}} + Q_{\text{food}} = 10.3 + 69.4 = 79.7 \text{ kJ}$$

Account for System Inefficiencies (Assume 20% Losses)

Let system efficiency $\eta = 80\% = 0.8$

$$Q_{\text{total}} = \frac{Q_{\text{Useful}}}{\eta} = \frac{79.7}{0.8} = 99.6 \text{ kJ}$$

2.1.3 Fuel Quantity Estimation

(a) Charcoal Requirement

Charcoal has an average lower heating value (LHV) of ~28,000 kJ/kg (Oladeji, 2019).

The required charcoal mass m_c to generate Q_{total} is:

$$m_c = \frac{Q_{\text{total}}}{\text{LHV}} = \frac{99.6}{28,000} \approx 0.003557 \text{ kg} \approx 3.56 \text{ g}$$

Assuming losses due to heat transfer inefficiencies and open combustion (actual charcoal ovens lose ~75–85% energy), a conservative overall efficiency of 20% is used:

$$m_c = \frac{Q_{\text{total}}}{\text{LHV}} = \frac{99.6}{0.2 \times 28,000} \approx 0.001779 \text{ kg} \approx 1.78 \text{ g (Per cycle)}$$

(b) LPG Requirement

LPG (Propane-Butane mix) has an LHV of approximately 46,000 kJ/kg. At a burner efficiency of 60% (due to better control and combustion):

$$m_{\text{LPG}} = \frac{Q_{\text{total}}}{0.60 \times 46,000} = \frac{99.6}{27,600} \approx 0.003609 \text{ kg} \approx 3.61 \text{ g}$$

Estimated Duration of LPG Use

To estimate how long this LPG amount would last, based on a practical burner's gas consumption rate. The following were assumed:

- LPG burner consumption Assume moderate rate: 0.3 kg/hr = 300 g/hr
- Each baking cycle (or heat requirement to reach 200°C) requires 99.6 kJ.
- To sustain oven operation for 1 hour, either for continuous baking or multiple cycles.
- The oven cycles on and off but maintains average temperature — meaning some heat input is needed continuously to maintain temperature, not just reach it once.

Now, to find time (t) to consume 3.61 g:

$$t = \frac{3.61}{300} \times 60 = 0.72 \text{ minutes} = 43.32 \text{ seconds}$$

If 3.61 g of LPG lasts 43.32 seconds, then:

Number of 43.32 second intervals in 1 hour =
 $\frac{3600}{43.32} \approx 83.10$

Now multiply that by 3.61 g:

$LPG\ required = 83.10 \times 3.61 = 23g$

To operate the oven continuously for 1 hour, based on the energy demand of 2.16 g per 26 seconds, you would need approximately 23 g of LPG, or 0.023kg.



Figure 3. Fabricated dual-energy source baking oven

Results and Discussions

The developed oven was put to the test to assess how well it performed in terms of heat retention, energy efficiency, and even temperature distribution. Its suitability for small-scale baking was also evaluated. Trials using both charcoal and LPG were conducted, and the results were carefully analysed and compared based on key performance indicators.

3.1 Heating Rate and Time to Reach Baking Temperature

The oven was tested to see how quickly it could reach the ideal baking temperature range

of 180–250 °C. With LPG, it took about 9 minutes to hit 180 °C, while using charcoal took around 16 minutes to reach the same temperature. This difference is mainly due to LPG's faster and more controllable combustion, which allows heat to build up more quickly, unlike charcoal, which heats up more gradually.

3.2 Maximum Temperature Attainable

With both energy sources, the oven successfully achieved the designed maximum internal temperature of 250 °C. However, LPG maintained more stable temperature

conditions with less fluctuation due to its precise control via the regulator valve, whereas charcoal showed wider thermal variation, particularly during the ignition and reloading stages.

3.3 Temperature Distribution Uniformity

Thermocouples were placed at the top, middle, and bottom layers of the baking chamber to assess heat distribution. The LPG-powered test recorded an average temperature deviation of $\pm 10^\circ\text{C}$, while the charcoal-fired test showed a wider deviation of $\pm 18^\circ\text{C}$. The higher uniformity in LPG mode is due to its more evenly distributed flame and steady fuel supply.

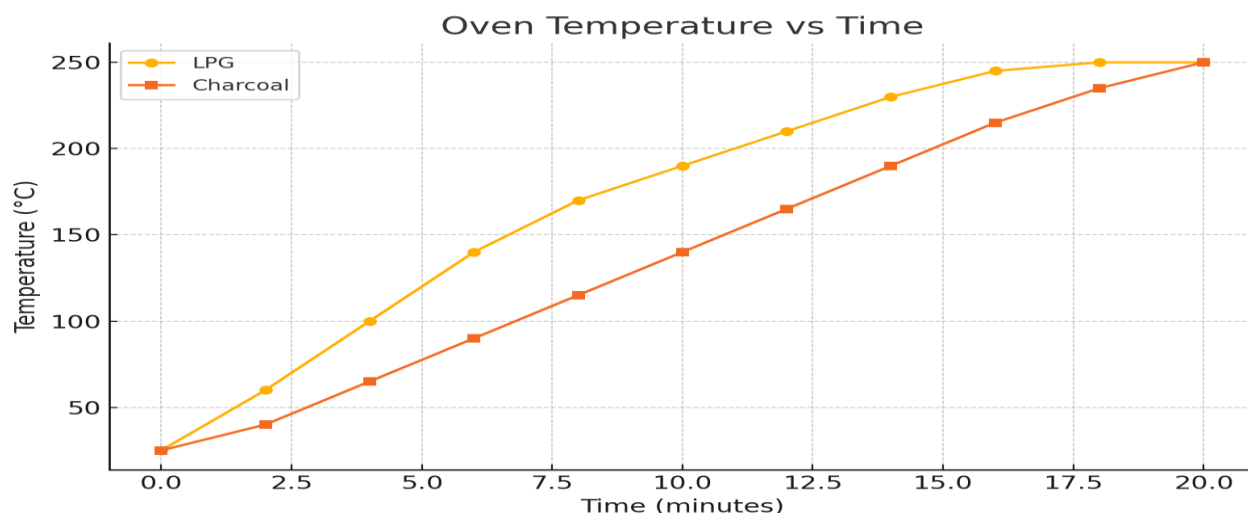


Figure 4: Oven Temperature vs. Time

3.4 Thermal Efficiency

Thermal efficiency was evaluated using the standard water boil test, which determines the ratio of useful heat absorbed by the water to the total energy input from fuel consumption.

(a) **Charcoal mode:** The thermal efficiency was calculated at 22.3%, a value that is consistent with performance ranges typically reported for solid-fuel ovens.

(b) **LPG mode:** A higher efficiency of 31.5% was obtained, attributable to cleaner combustion characteristics and reduced heat losses during operation.

These findings are in agreement with reported values for comparable small-scale dual-fuel systems (Aremu *et al.*, 2021; Adeyemi and Akinoso, 2018), thereby reinforcing the reliability of the results.

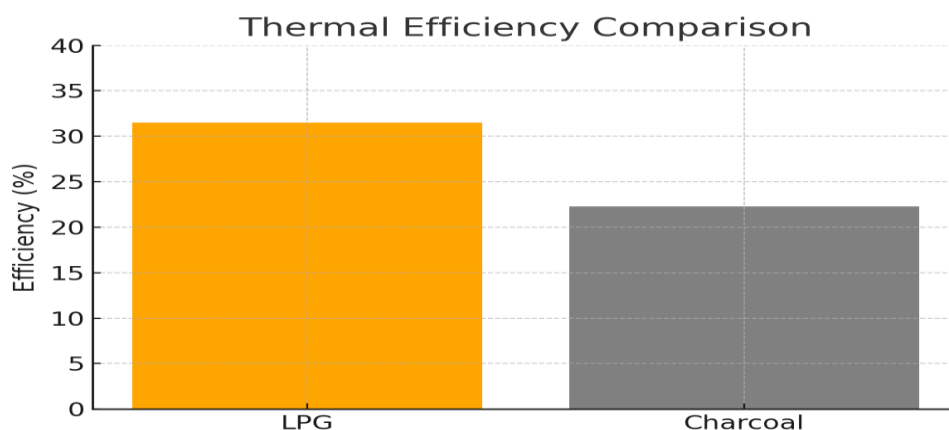


Figure 5: Thermal Efficiency Comparison

3.5 Fuel Consumption

Fuel consumption was measured over a one-hour test period to provide a basis for evaluating the operational performance and comparative efficiency of the two fuel modes.

- a) **LPG:** 0.38 kg/hour
- b) **Charcoal:** 0.9 kg/hour

Although charcoal is typically more affordable and widely accessible, its higher rate of consumption and relatively lower thermal efficiency render LPG the more economical option when evaluated in terms of energy output per unit mass.

3.6 Experimental Results for Baking Performance Using Meat Pie and Fish

To validate the performance of the dual-energy baking oven under practical conditions, baking trials were conducted using meat pies and whole fish as representative food samples. These experiments were designed to assess the oven's effectiveness in real-world applications by examining product quality, baking time, heat distribution, and energy utilization during typical cooking operations.

3.6.1 Baking Meat Pie

A batch of twelve medium-sized meat pies, each weighing approximately 150 g, was evenly arranged on the oven trays and baked under both LPG and charcoal operating modes. This setup provided a consistent basis for comparing baking performance across the two energy sources. When powered by LPG, the oven was preheated to 200 °C and

maintained at that temperature throughout the baking process. The meat pies were fully baked in 25 minutes, exhibiting uniform browning, a crisp and golden crust, and well-cooked filling. The internal temperature of the pies reached approximately 92 °C, ensuring food safety and proper doneness. The LPG mode demonstrated consistent thermal distribution, resulting in even colour, pleasant aroma, and desirable texture.

In contrast, the charcoal-powered mode required a longer time of about 35 minutes to achieve similar baking results. Although the pies were acceptably cooked, the browning was less uniform, and some edges became overly browned. The crust also appeared slightly drier, likely due to inconsistent heat distribution and localized hotspots. Some pies needed repositioning during baking to avoid undercooked areas or overexposure to radiant heat.

3.6.2 Grilled Fish Test

For the fish grilling test, two whole catfish (weighing 450 grams each) were seasoned and placed on perforated trays for roasting. Using LPG at a steady temperature of 220 °C, the fish were fully grilled in 30 minutes, reaching an internal temperature of around 75 °C—enough to ensure they were thoroughly cooked. The LPG provided consistent heat, resulting in evenly grilled fish with a nicely seared exterior, moist interior, and minimal smoke or odour.

When charcoal was used, grilling took longer—about 40 minutes. While the fish were properly cooked, the heat was less evenly distributed. The surface developed a characteristic smoky aroma, which is often preferred in traditional cooking. However, some parts of the fish were slightly overcooked, while others were underdone. The uneven temperature distribution in charcoal mode contributed to greater moisture loss, which in turn affected product texture in certain sections. In contrast, the LPG mode offered more precise control over cooking time and temperature, resulting in superior overall product quality. Nevertheless, the charcoal mode yielded outcomes that remained acceptable, particularly for consumers who value the distinctive smoky flavour often associated with traditional local dishes.

Table 4: Summary of Baking Performance Using Meat Pie and Fish

Parameter	LPG Mode	Charcoal Mode
Meat Pie Bake Time	25 mins	35 mins
Fish Roast Time	30 mins	40 mins
Heat Uniformity	High	Moderate
Browning Consistency	Uniform	Uneven
Product Quality	Excellent	Acceptable
Flavour Profile	Clean, Natural	Smoky, Traditional
Smoke/Odour	Minimal	Moderate-High

Conclusion

This study has demonstrated the successful design, development, and performance assessment of a dual-energy baking oven utilizing both charcoal and liquefied petroleum gas (LPG), tailored for domestic use and small-scale food enterprises. The system was engineered to provide flexibility in fuel choice,

enhance thermal performance, and address the practical demands of local food processing. Experimental evaluation showed that the LPG mode outperformed charcoal in most aspects, achieving faster heating, more stable temperature regulation, and higher fuel efficiency. Specifically, LPG recorded a thermal efficiency of 31.5% with a temperature variation of ± 10 °C, whereas charcoal achieved 22.3% efficiency with a wider variation of ± 18 °C. Practical baking trials with meat pies and whole fish further confirmed the advantages of LPG, which produced more uniform results in shorter baking times. Nonetheless, charcoal remained a viable alternative, particularly in off-grid settings, offering the added benefit of a traditional smoky flavour alongside its broader availability and lower cost.

Overall, the dual-fuel configuration enhances versatility and resilience by enabling users to switch between energy sources according to availability and affordability. This makes the oven especially well-suited for rural households, micro-bakeries, street food vendors, and small-scale enterprises operating in developing communities.

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