

A Techno-Economic Comparison of CST and Conventional Cooking Technologies in West Africa

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Abstract. Clean and affordable cooking remains a critical challenge in sub-Saharan Africa, where traditional biomass-based methods create health, environmental, and economic burdens. This study compares the economic viability of Concentrated Solar Thermal (CST) cookers, Fresnel Lens and Parabolic Trough Collector (PTC), with traditional charcoal stoves in rural Nigeria and Ghana using the Levelized Cost of Cooking a Meal (LCCM). While charcoal stoves offer the lowest short-term cost (\$0.07628/meal), CST cookers become more economical over time, with the Fresnel Lens achieving an LCCM of \$0.1432/meal over a 30-year lifespan. The PTC offers flexibility but has a higher cost due to its advanced design. The study emphasizes the potential health and environmental benefits of CST cookers, along with policy recommendations for overcoming adoption barriers through subsidies and innovative financing.

Keywords: Concentrated Solar Thermal (CST), Levelized Cost of Cooking a Meal (LCCM), Solar Cookers, Solar Heat for Industrial Processes (SHIP)

1. Introduction

In the context of sub-Saharan Africa, particularly in Nigeria and Ghana, the challenges of energy access are exacerbated by significant health, economic, and environmental issues arising from common cooking practices. Nigeria, boasting a population of 216 million and the status of being Africa's largest economy, together with Ghana, noted for its rapid economic growth and a population of 32 million, serve as prime examples of regions where nearly half of the population lives in rural areas without access to grid energy. The dependence on traditional open-fire cooking methods in these areas not only precipitates a health crisis due to household air pollution but also hampers economic activities due to the extensive time and cost required for fuel collection. This disproportionately affects women, who predominantly manage cooking tasks and consequently face serious health risks, including respiratory diseases.

Globally, residential energy consumption ranks as the third largest sector of total energy use, with a considerable share attributed to cooking in developing countries. Conventional

cooking methods have numerous detrimental effects. According to IEA (2018) data, about 1 billion people in sub-Saharan Africa lack access to clean cooking solutions, leading to over 500,000 deaths annually. The inefficiencies associated with traditional biomass usage for cooking, primarily with wood and charcoal, underscore the urgent need for alternative solutions that can mitigate the economic and health burdens on households.

Cooking technologies in these regions range from basic firewood- and charcoal-burning stoves to advanced and efficient charcoal models. The World Health Organization categorizes biomass cookstoves into various tiers based on emission levels and efficiency [1]. Despite the known health hazards posed by unimproved stoves, widespread obstacles hinder the adoption and sustained, exclusive use of improved models. Key barriers include cost considerations, unreliable supply chains, social acceptability, and the educational, socio-economic, and demographic backgrounds of households. The cost of clean cooking is split into two main components: the initial expense of acquiring the stove and the ongoing cost of fuel. The upfront cost of the stove remains a significant obstacle for low-income families. For instance, findings from certain areas in India reveal that even after initial stove adoption, as many as 24% of households do not purchase necessary fuel refills, illustrating a crucial maintenance cost barrier [2,3]. This situation underscores the rationale for this research, highlighting the potential for solar cookers to offer low maintenance costs.

This paper addresses the urgent call for innovative technological solutions by evaluating the economic viability of Concentrated Solar Thermal (CST) technologies, specifically the Fresnel Lens Cooker and the Parabolic Trough Collector (PTC) with energy storage capabilities. These technologies are part of a broader initiative under an Innovate UK project focused on developing hybrid energy solutions for solar cooking and low-grade electricity using Thermoelectric Generators (TEGs). Employing a techno-economic analysis, including the calculation of the Levelized Cost of Cooking a Meal (LCCM), this study aims to provide a comparative assessment of these CST cookers against traditional cooking methods in communities of Bauchi State, Nigeria, and the Central Region of Ghana.

2. Methodology

This study examined the usage and economic impact of traditional charcoal-based cookers and solar cooking technologies in West African regions. The potential benefits include the technical usage (time to prepare a meal, commodity to use the system, environment friendly) as well as the economic side (cost of cooking a meal, time invested, proximity of fuel provision). For this purpose, a conventional charcoal cooking device has been used and tested along the two CST developed technologies (PTC and Fresnel Lens) to compare the performance of different devices.

Prior to deployments the cookers critical data collection was conducted through surveys in collaboration with IBEDA in Nigeria & Conlon's Kitchen Ghana, focusing on user demographics, economic factors, and cooking habits. The Central Region for instance, known for its heavy reliance on biomass fuels, primarily charcoal, was selected with 302 respondents, predominantly female (over 90%) and most (65%) earning below \$37 monthly, participating in the survey. Economic analysis included examining fuel costs and usage patterns, with less than 48% of households spending under \$9 monthly on charcoal, while an average of 38% spent around \$13 monthly. Additional costs for transportation of fuel were not considered, with 29% using commercial transport for fuel acquisition, underscoring the economic burden of traditional fuel use. Similar data is found for the specific communities observed in the Nigerian region. A full social study has been integrated in this study to highlight the baseline situation of local communities). In these regions, the fuel consumption was tracked and cooking times for specific meals, standardized as 1.3L of water boiled (for tea or porridge a common meal in both regions). These data points were used to calibrate the energy required for a standard meal across different cooking technologies.

The performance of two types of CST technologies, the PTC the Fresnel Lens Cooker, was evaluated. In Figure 1a&b CST systems with integrated energy storage is shown for the Fresnel lens and PTC respectively.



Figure 1. a. CAD model and built version of the PTC Cooker **b.** CAD and built version of the Fresnel cooker.

The Fresnel system uses a series of flat Fresnel lenses to concentrate sunlight directly onto a cooking surface. It has a lower upfront cost than the PTC but lacks the heat retention capacity provided by an indirect cooking method. The Fresnel lens system includes a storage tank to extend cooking times when solar radiation is inconsistent. The PTC system uses parabolic mirrors to focus sunlight onto a receiver tube containing a heat transfer fluid (HTF), such as the Shell Thermia Oil B. The PTC's integrated HTF storage system allows for indirect cooking. However, the upfront cost of the PTC system is higher. Both technologies have an assumed lifespan of 20 years with an annual operation and maintenance (O&M) cost of \$10. Technical specifications of the cookers and storage tanks are shown in Table 1.

Table 1. Specifications of PTC and Fresnel Lens

Description	PTC Spec	Fresnel Lens Spec
Aperture area (m ²)	2	1.4
Receiver tube length (m)	2	-
Inner steel tube diameter (mm)	40	-
Outer glass tube diameter - vacuumed (mm)	90	-
Tank Material	Mild Steel	Mild Steel
Cooker Top	Finned Stainless steel	Finned Aluminium
Tank Thickness (mm)	5	2
Total Tank Volume (Litres)	15	40
HTF Volume - Shell Thermia Oil B (Litres)	10	25
Total Cost (\$)	3900	1700

Field testing was conducted for the Fresnel lens cooker to determine its performance in real-world conditions, while simulation and computational fluid dynamics (CFD) analysis using SolidWorks was employed to estimate the performance of the PTC cooker. The Fresnel lens test measured the time required to bring 1.3 liters of water to a boil, whereas the PTC simulation modeled heat transfer performance under varying solar flux conditions.

To assess the economic viability of each cooking technology, the LCCM(\$/meal) [3,4] was calculated for both the CST and traditional charcoal cookers. The LCCM provides a comparative measure of the cost per meal, accounting for initial investment, operational expenses, and fuel consumption over the lifetime of the stove. The LCCM was calculated using the following formula shown in equation 1 [3]:

$$LCCMt = \frac{F_{ct} \times E_m}{\eta_s} + \frac{\sum_{t=1}^n \frac{I+O\&M}{(1+r)^t}}{\sum_{t=1}^n \frac{Ml}{(1+r)^t}} \quad (1)$$

where F_{ct} is the fuel cost in USD per MJ at time t , E_m is the energy required for cooking a meal in MJ, η_s is the stove efficiency, I is the investment cost, O&M are the operation and maintenance costs, Ml is the number of meals cooked per period t , n is the lifespan of the stove, r is the discount rate (20% used for the region). The burning rate of the fuel (ρ) is calculated (equation 2 [3]) as the mass of the fuel divided by the cooking time (ct), which determines the energy required per meal (E_m):

$$E_m = LHV_{fuel} \times \rho \times ct \times \eta_s \quad (2)$$

The LCCM for traditional charcoal stoves was calculated based on field data, with a focus on fuel consumption rates, stove efficiency (30%), and typical stove lifespans (10 years). For the Fresnel Lens and PTC cookers, the LCCM was derived using their respective upfront costs, energy storage benefits, and maintenance expenses over 20- and 30-year lifespans.

These equations are foundational for conducting a full economic analysis of cooking technologies, and they will be used to compare the cost-efficiency of traditional charcoal cookers and the Fresnel Lens and PTC Solar Cookers within the specific context of the similar regions. A sensitivity analysis was performed to test the robustness of the results under different discount rates and lifespans. This analysis helps assess how changes in key variables, such as investment costs and cooking frequency, affect the LCCM for each technology.

3. Results

The field survey and testing in both Nigeria and Ghana focused on traditional charcoal stoves as the Fresnel Lens and PTC Cookers are built and tested in UK. The initial tests aimed to determine fuel consumption, time to boil, and the amount of energy required to cook a standard meal, boiling 1.3 liters of water representing a simplified benchmark.

The charcoal stove test showed that boiling 1.3 litres of water took approximately 10 minutes when using 180g of charcoal (cf Fig 2). Two meals, which required 360g of charcoal, took about 20 minutes to cook. The stove's efficiency was recorded at 30%, consistent with previous studies on traditional stoves in sub-Saharan Africa [2].

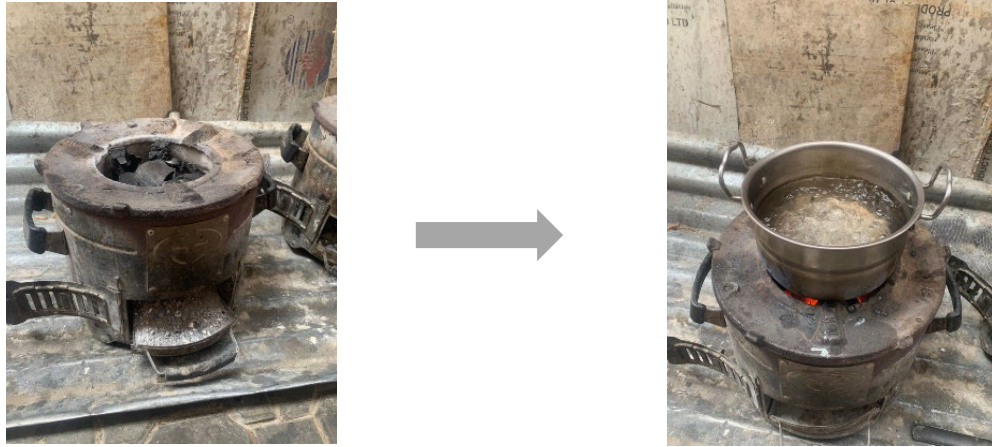


Figure 2. Typical charcoal stove in region subjected to water boiling tests.

The Fresnel lens cooker test reached boiling point in 15 minutes when cooking the same amount of water as shown in Figure 3. This indicates a slower performance compared to the charcoal stove, which can be attributed to variations in solar intensity during the testing period. However, the cooker demonstrated significant fuel savings, as it relies entirely on solar energy.

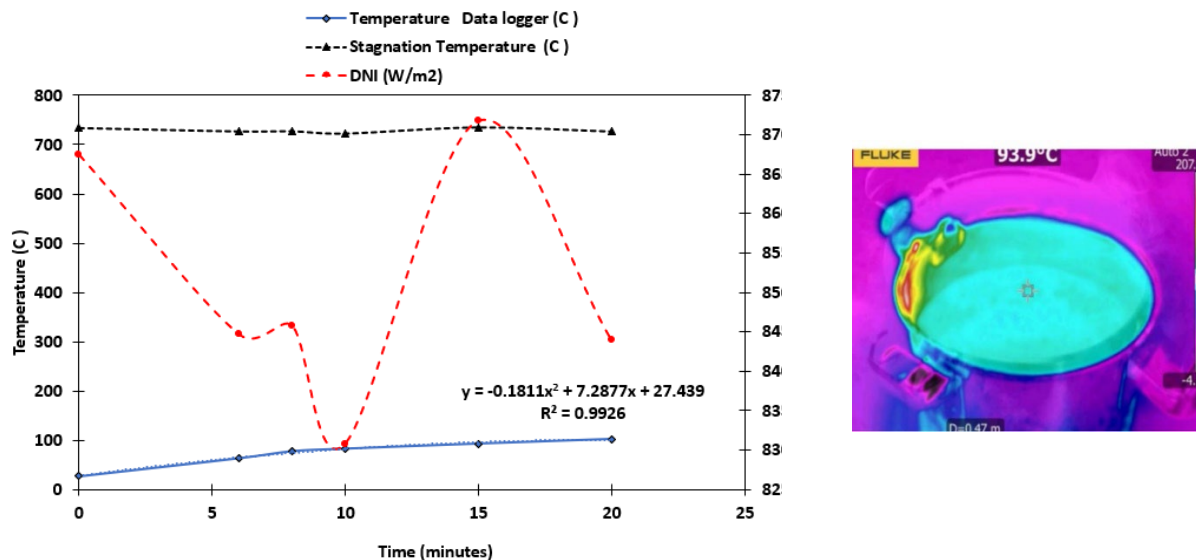


Figure 3. Field test results from Fresnel lens field test, thermal image of boiling pot.

Although built, field testing of the PTC has not been concluded due to seasonal weather shift for optimal tests in the UK. Computational Fluid Dynamic (CFD) was thus used for the thermal modelling. The simulation focused on the time required to boil 1.3 liters of water using

indirect cooking via a thermal oil storage system. The simulation was based on an average solar flux of 1500 W/m².

The PTC simulation showed that the boiling point was reached in approximately 1100 seconds (about 18 minutes) with average HTF temperature in the tank at 112°C. The thermal oil temperature in the storage tank reached and maintained 112°C during the cooking process, allowing for consistent heat transfer even during fluctuating solar radiation. The simulation indicated that, once heated, the PTC could maintain sufficient cooking temperatures allowing for multiple meals to be cooked without additional energy input (cf Fig 4).

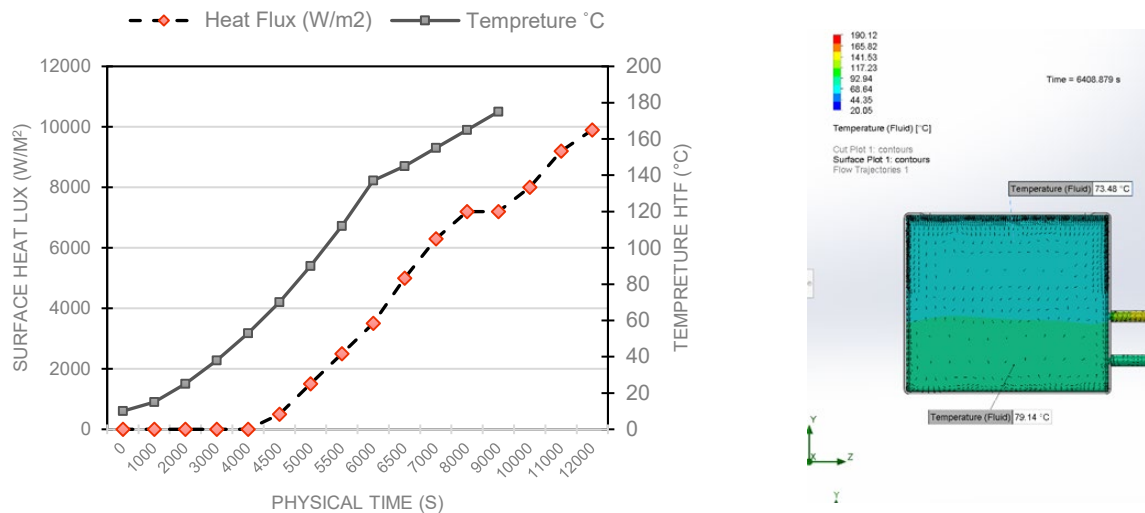


Figure 4. Simulated results and snapshot of temp contours of the model.

3.1 LCCM Analysis

The LCCM was calculated for the traditional charcoal stove, the Fresnel Lens Cooker, and the PTC over a range of cooking durations and meal frequencies. The LCCM accounts for initial investment costs, ongoing maintenance costs, and fuel consumption over the expected lifespan of each cooking technology. The results, summarized in Figure 5 illustrates the LCCM under different cooking durations, meal frequencies, and lifespans.

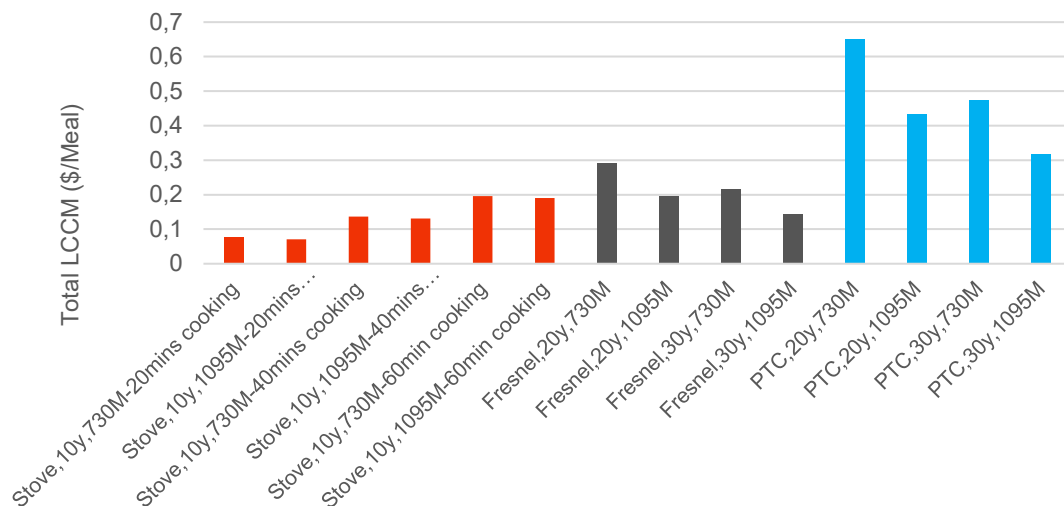


Figure 5. Total LCCM by cooker type, lifespan, and meals per year (M).

The LCCM for the charcoal stove was calculated for different cooking durations and meal frequencies. For households cooking 730 meals/year the LCCM was \$0.07628/meal for a 20-minute cooking duration. However, as cooking times and the number of meals increased, fuel consumption rose, and the LCCM increased accordingly. For a 60-minute cooking duration, the LCCM increased to \$0.19616/meal due to the larger quantity of charcoal required.

For households cooking 730 meals/year, the Fresnel Lens Cooker had an LCCM of \$0.2916/meal over a 20-year lifespan. As the lifespan extends to 30 years, and the number of meals increases to 1095/year, the LCCM decreases to \$0.1432/meal. The zero-fuel cost is a major factor in reducing the overall LCCM as the system's lifespan increases.

The PTC Cooker had the highest LCCM at \$0.6514/meal with 730 meals/year over a 20-year lifespan, largely due to its high upfront cost. As the lifespan extends to 30 years and the number of meals increases to 1095/year, the LCCM drops to \$0.3167/meal.

The results of the LCCM analysis indicate that the charcoal stove is the most cost-effective option in the short term, especially for households with lower cooking frequencies and shorter cooking durations. However, this low LCCM comes with significant environmental and health costs, which are not reflected in the LCCM figures study. The Fresnel Lens Cooker, though initially more expensive, becomes more economically viable over time, particularly for households that cook three meals per day or have access to prolonged sunlight. The zero fuel cost and low maintenance requirements make it a highly attractive option for long-term use. Its LCCM decreases dramatically as the number of meals and lifespan increases. The PTC Cooker presents the highest LCCM, largely due to its complex design and higher initial cost. However, the PTC's advantage lies in its ability to provide consistent cooking capabilities even when solar energy is intermittent, thanks to its larger integrated storage.

4. Conclusion

This study has provided a comprehensive comparison of the economic and performance viability of traditional charcoal stoves and CST cookers, specifically, the Fresnel Lens Cooker and the PTC for rural communities in West Africa. The findings highlight the potential for CST technologies to offer a sustainable and cost-effective alternative to traditional cooking methods.

The LCCM analysis revealed that, in the short term, the traditional charcoal stove remains the most affordable option with an LCCM as low as \$0.07628/meal for basic cooking needs. However, this cost advantage comes with significant externalities, including severe health and environmental impacts, which are not factored into the LCCM calculation but are critical considerations for long-term sustainability.

In contrast, CST technologies, though associated with higher initial costs, exhibit substantial long-term cost advantages, particularly when cooking frequency and cooker lifespan are maximized. The Fresnel Lens Cooker, with a zero-fuel cost and a potential LCCM as low as \$0.1432/meal when used over a 30-year period with frequent cooking, demonstrates the economic viability of solar cooking for households that can afford the upfront investment. Similarly, the PTC, despite its higher initial cost, also shows significant promise for communities requiring flexibility in cooking due to its integrated energy storage system, achieving an LCCM of \$0.3167/meal under optimal conditions. Furthermore, the CST units tested were built in the UK, where the trials were conducted, possibly extending the final costs of the units. It is expected that the costs of locally manufactured units in the region of deployments will be lower, further enhancing their feasibility.

While the charcoal stove has the lowest upfront and short-term costs, it carries significant hidden costs related to indoor air pollution, deforestation, and climate change. Households that rely on charcoal cooking are at higher risk of respiratory diseases due to prolonged exposure

to smoke. Additionally, the environmental degradation associated with charcoal production and use poses long-term risks to biodiversity and contributes to CO₂ emissions.

One of the key challenges for CST technologies is their high upfront cost, which may present a barrier for low-income households in West Africa. However, innovative financing models such as community-based ownership, government subsidies, or microfinancing schemes could reduce this burden. For instance, in households in the region that have three meals a day, these cookers could be used in community settings where neighbours or local groups utilize staggered cooking, potentially doubling or more the meals cooked, thereby reducing the LCCM and enhancing ownership through shared costs.

Additionally, the adoption of CST technologies may be enhanced by addressing social and cultural barriers, improving awareness of the long-term cost savings and health benefits, and ensuring reliable supply chains for spare parts and maintenance services.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article. Additional information on data can be made available upon reasonable request from the corresponding author.

Author contributions

Zaharaddeen Ali Hussaini: Conceptualization; writing – original draft; formal analysis; investigation; resources. Mounia Karim: Conceptualization; writing – review and editing. Khalifa Aliyu Ibrahim: Conceptualization; resources; investigation; writing – review and editing. Zhenhua Luo: Resources; supervision; formal analysis; project administration; writing – review and editing. Christopher Sansom: Supervision; formal analysis; project administration; writing – review and editing. Tugba Gurler: Writing – review and editing; Johnson Okeniyi: Investigation; Resources. David Akraa: Investigation; Resources. Saifullah Ali: Investigation; resources.

Competing interests

The authors declare that they have no competing interests.

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