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ORIGINAL RESEARCH ARTICLE

Techno-economic analysis of clean cooking technologies and fuels in Uganda

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ABSTRACT

Access to clean, affordable, and efficient cooking energy is a key development challenge in Uganda, with over 90% of households and institutions relying on traditional biomass fuels. This study was focused on techno-economic assessment of cooking technologies and fuels through Controlled Cooking Tests (CCTs), surveys, and interviews across household and institutional settings to evaluate fuel consumption, cooking time, cost, and user preferences across wood, charcoal, briquettes, LPG, and electric stoves. The results showed that electric hot plates and LPG stoves were the most energy-efficient, consuming 10.42 MJ and 13.28 MJ, respectively, cooking of 1 kg of beans compared to 38.81 MJ for improved wood stoves and 102.44 MJ for traditional three-stone fires. Cooking time, the improved institutional wood stove was the fastest (129 min), followed by LPG (151 min), traditional stoves (153 min), and electric hot plates (174 min). Fuel cost per kg of beans cooked was highest for LPG (Ugx 5,506) and electricity (Ugx 4,393), while improved briquette stoves were the cheapest (Ugx 302), though their adoption remains limited due to availability issues. Improved biomass stoves demonstrated up to 62% energy savings compared to traditional devices, offering a cost-effective and scalable transition option. This study provides the first comprehensive performance comparison across multiple fuel-stove combinations in Uganda and highlights critical trade-offs between energy efficiency, cost, and accessibility. Strategic policy actions including targeted subsidies, investment in clean fuel supply chains, and behaviour change campaigns are recommended to accelerate adoption and support Uganda's energy, climate, and development goals.

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INTRODUCTION

Uganda has a unique potential of alternative renewable energy resources including hydropower, solar, geothermal, wind and biomass (Eze, 2024). In the last 10 years, Uganda has focused her energy sector investment on increasing energy access by increasing energy supply. In light of this, this study conducted an experiment on available energy efficient solutions in Uganda focusing on their performance, availability, affordability and access to fuels. This study unveils the rate of biomass consumption and cost benefit analysis by large institutions and households which guided a recommendation of the choice of an appropriate technology to install when the institutions and households are making decisions on energy and technologies to install (Eze, 2024). Access to modern and clean energy services is a necessary precondition for achieving development goals that extend far beyond the energy sector, such as poverty eradication, access to clean water, improved public health and education, women's empowerment and increased food production (MEMD, 2015). Uganda through the Ministry of Energy and Mineral Development (MEMD) is mandated "to establish, promote the Development, Strategically Manage and Safeguard the Rational and Sustainable Exploitation and Utilization of Energy and Mineral Resources for Social and Economic Development". In line with this mandate, Uganda Vision 2040 (Uganda Vision, 2007) states that "Ugandans aspire to have access to clean, affordable and reliable energy sources to facilitate industrialization (MEMD, 2015; Abd-Elfaraga & Langoyab, 2016; Chagunda *et al.*, 2017).

Uganda's Vision 2040 and National Development Plan IV (NDP IV) recognize clean energy access as a key enabler for socio-economic transformation. These national frameworks emphasize the need to promote clean cooking technologies as part of efforts to improve public health, reduce environmental degradation, and increase energy security. Furthermore, Uganda's commitments under the Sustainable Development Goals (SDGs)—especially Goal 7 (Affordable and Clean Energy), Goal 3 (Good Health and Well-being), and Goal 13 (Climate Action)—reinforce the urgency of accelerating the shift to clean cooking solutions (Masuda *et al.*, 2021). Use of clean fuels and improved technologies has multiple benefits; they reduce heavy reliance on wood fuel as the main source of fuel for cooking hence protecting the environment, has potential to improve the health of the household or institutional kitchen users through reduced exposure to smoke from Combustion of biomass. Multiple alternative energy sources (clean fuels) have been popularized and offer higher energy content (as compared to the traditional) but also offer additional benefits in handling, transportation, storage and ignition. The improved and clean cooking devices offer added advantages of fuel savings, increasing efficiency, reduced cooking time, stability, durability, improved aeration among others (Yunusa *et al.*, 2023; Mlowa *et al.*, 2024).

The analysis is applied across two primary user groups: large institutions (such as schools, hospitals, and correctional facilities) and households, recognizing their different cooking needs, usage patterns, and budgetary limitations. The study provides evidence-based insights to guide policy formulation, institutional planning, and investment decisions in Uganda's energy sector. By quantifying the trade-offs between traditional and clean cooking options, the findings will help highlight scalable and economically viable pathways for transitioning to modern energy solutions. In the context of Uganda's growing population, rapid urbanization, and increasing demand for sustainable development, this research contributes to ongoing national efforts to enhance energy access, reduce poverty, and protect the environment. It underscores the importance of integrating clean cooking into broader energy planning and policy, particularly as Uganda positions itself to harness its demographic dividend and build a climate-resilient economy (Kaoma & Gheewala, 2021; Schöne *et al.*, 2023). This paper presents a techno-economic assessment of improved cooking technologies and clean fuels in Uganda, using a "kitchen laboratory" cost-benefit analysis approach. By simulating real cooking scenarios within a controlled environment, the study measures the efficiency, fuel consumption, emissions, operational costs, and overall cost-effectiveness of selected technologies.

Uganda faces a persistent challenge in transitioning from traditional biomass-based cooking methods to cleaner, more efficient energy options. Despite growing concerns about health risks, environmental degradation, and inefficient energy use, most households and institutions continue to rely on firewood and charcoal using traditional stoves. Biomass fuels dominate Uganda's energy mix, accounting for over 90% of cooking energy, with widespread use of inefficient technologies that increase pressure on forests and contribute to indoor air pollution. While improved cook stoves and alternative fuels are available, their adoption remains limited due to cost, accessibility, and behavioral factors. This study provides critical evidence on the performance, fuel use, and cost-effectiveness of various cooking technologies under real-world conditions. The results support informed policy-making and targeted interventions aimed at improving energy access, public health, and forest conservation in Uganda. Previous studies have focused largely on household energy use, with limited comparative data across multiple stove-fuel combinations in both household and institutional contexts. This study fills that gap by evaluating a range of technologies traditional, improved biomass, LPG, electric, and briquette-based using standardized testing and cost analysis (Kumar & Igdalsky, 2019; Hou *et al.*, 2022; Acheampong & Opoku, 2023; de Sousa Venega *et al.*, 2023). The aim of this study was to assess the fuel efficiency, cost implications, and user barriers of different cooking technologies to guide cleaner energy adoption among households and institutions, and to support Uganda's transition toward sustainable and equitable energy systems.

MATERIALS AND METHODS

Study design

This study employed a mixed-methods participatory approach, integrating methodological paradigm triangulation to capture both quantitative and qualitative dimensions of energy use and cooking technologies in Uganda. A convergent parallel design was adopted to ensure the simultaneous collection and validation of diverse datasets, enhancing analytical robustness (Aguado Loi *et al.*, 2017).

Quantitative data collection

A structured questionnaire was administered to 789 respondents, comprising 237 institutional representatives (30%) and 552 household respondents (70%) from four regions of Uganda. Study was conducted in Kampala, Wakiso, Mukono, Mubende, Masaka, Jinja, Mbale, Soroti, Mbarara, Bushenyi, Gulu, and Lira districts. Institutions sampled were predominantly urban and peri-urban (84%) and represented sectors such as bakeries, breweries, hospitals, hotels, security agencies, and schools. Household respondents were drawn from both rural (47.2%) and urban/peri-urban (52.8%) settings. Data collection utilized electronic tools, with all survey instruments administered via tablet-based software to ensure accuracy and minimize physical contact. In cases where direct engagement was constrained, remote methods such as phone interviews, email, SMS, and WhatsApp messages were employed. FGDs with urban participants were conducted via Zoom, while in-person FGDs in rural areas adhered to strict social distancing protocols, limiting participation to a maximum of ten respondents per session (Aguado Loi *et al.*, 2017).

Qualitative data collection

In-depth qualitative insights were gathered through five focus group discussions (FGDs), three with institutional participants and two with household participants. The FGDs, facilitated by trained researchers, explored themes related to energy adoption, accessibility, and performance. Additionally, key informant interviews (KIIs) were conducted with policymakers, industry experts, and energy practitioners to contextualize survey findings (Akhter, 2022). A document analysis of policy and regulatory frameworks was also undertaken to triangulate insights from primary data.

Controlled Cooking Tests (CCTs)

Performance assessments of six stove models were conducted in collaboration with the Centre for Integrated Research and Community Development Uganda (CIRCODU), adhering to the Controlled Cooking Test Protocol v2.0. Specific fuel consumption and cooking time were compared between improved cooking technologies and traditional stoves, with each stove model tested three times by two independent cooks, resulting in a total of 36 controlled tests. Baseline comparisons were made using a three-stone fire and a metallic charcoal stove (Arora *et al.*, 2014; Gebreegziabher *et al.*, 2018; Tesfay *et al.*, 2024).

Data management and analysis

Quantitative data was extracted from a secure server, cleaned, and analysed using STATA 16 (Stata Corp, 2019), applying descriptive and inferential statistical methods. Qualitative data from FGDs and KIIs was transcribed, coded using ATLAS.ti software and analysed thematically to identify patterns and relationships. A deductive-inductive approach was employed to merge emerging themes with predefined theoretical constructs. To enhance analytical rigor, methodological, data, and investigator triangulation techniques were employed, ensuring the reliability and credibility of findings.

Ethical considerations

The study adhered to ethical research standards, including obtaining informed consent from participants, ensuring data confidentiality, and securing approvals from relevant institutional review boards. Measures were taken to anonymize responses and uphold the integrity of the research process.

RESULTS AND DISCUSSION

The controlled cooking tests

The study performed Controlled Cooking Tests (CCTs) in order to compare costs and benefits of the traditional and the improved cook stoves found in the markets and widely used by households and institutions. The tests were carried out in conformity with the Controlled Cooking Test Protocol version 2.0 of August 2004 by Rob Bailis and ISO 17025: 2017 (Doyle, 2024). Each of the stove samples shown in Table 1 was tested three times by the same cook to ensure uniformity in application of the protocols. A commonly prepared dish of beans was cooked on each of the stove samples. For each meal, 500g of beans was prepared with ingredients such as tomatoes, green pepper, onions, salt, Royco and water to make a replica of a typical meal (Arora *et al.*, 2014; Gebreegziabher *et al.*, 2018). Considering that different fuels were used for different stoves, a metric of MJ of energy/kg of food was adopted for specific fuel consumption. The results of these CCTs showed that improved institutional stoves consumed significantly less energy, averaging 2.1–2.6 MJ/kg of food, compared to traditional three-stone stoves which ranged between 4.5–5.3 MJ/kg. This nearly 50% reduction in fuel consumption not only highlights the superior thermal efficiency of improved stoves but also implies major cost savings and reduced emissions for large-scale users. One possible reason for this efficiency is the improved combustion design and insulation in modern stoves, which maximizes heat transfer and minimizes heat loss. These findings are consistent with (Gebreegziabher *et al.*, 2018; Skreiberg *et al.*, 2023), who reported 40–60% fuel savings from improved biomass cook stoves in Ethiopia and China, respectively.

For charcoal, firewood, and LPG fuel, the energy consumed per kilogram of food cooked was derived by multiplying the fuel heating value (MJ/kg) with the quantity of fuel consumed per kilogram of food cooked (Table 1). The lower heating values (LHVs) used are 29.5MJ/kg for charcoal, 17.3MJ/kg for wood, 21.0MJ/kg for briquettes, and 46.1MJ/kg for LPG. For electricity, the energy consumed per kilogram of food was derived by multiplying the stove power rating (1000J/s) with the cooking time (in seconds). This approach allows for the estimation of energy consumption in terms of food preparation, which is a critical aspect in Uganda where the reliance on various cooking fuels varies depending on the region, socio-economic status, and environmental sustainability. For instance, in rural areas, charcoal and firewood are often the dominant cooking fuels, while urban households are gradually shifting towards LPG and electricity (Astbury *et al.*, 2019). By calculating energy use per kilogram of food cooked, these metrics can help assess the environmental impacts of different cooking fuels, inform energy policy decisions, and contribute to sustainable energy planning for the country's development, especially considering the growing concerns over deforestation and the push for cleaner cooking technologies (Akter & Pratap, 2022; Sarpong *et al.*, 2023).

The Traditional Ceramic Stove used in urban areas, which burns charcoal and briquettes, shows some improvement in efficiency but still suffers from incomplete combustion and higher emissions compared to more modern stoves (Ochieng *et al*., 2013). The Improved Installed Household Stove (Rolena) uses firewood and offers a more efficient alternative to the three-stone stove, though performance can vary. The Mobile Improved Stove (using charcoal and briquettes), while more efficient, still poses risks of indoor air pollution if not used properly (Wafula *et al*., 2000). The Home Gas Stove, using LPG, is a cleaner and more efficient option, especially in urban areas, producing fewer emissions compared to biomass stoves. The Electric Hot Plate also offers a clean cooking option, though its environmental impact depends on the electricity source. The test methods outlined, such as using a weighing scale and moisture meter, ensure accurate data collection on fuel consumption and stove performance (Anozie *et al*., 2007; Bekkouche *et al*., 2023). Overall, tracking stove performance through these methods can guide future initiatives to improve cooking efficiency and sustainability in Uganda (Kumar & Igdalsky, 2019). These observations are consistent with recent global trends favoring clean energy cooking options. Studies such as (KC *et al*., 2020) and (Leary *et al*., 2021) highlight the importance of electricity access and grid decarbonization in maximizing the benefits of electric stoves. Standardized testing, as emphasized in this study, is also a recurring recommendation in newer literature to ensure comparability and inform policymaking. Therefore, electric and LPG stoves present scalable options, especially where grid reliability is improving, and should be integrated into Uganda's clean cooking strategy alongside rigorous performance tracking and emissions monitoring.

Table 1. Description of the Samples that were tested in the CCTs.

Name of stoves	**Traditional three-stone**	**Traditional Ceramic**	**Improved Installed Household Stove (Commonly known as Rolena)**	**Mobile improved Stove (size 2) / Charcoal & Briquettes**	**Home Gas Stove**	**Electric Hot Plate**
Quantity	1	3	1	3	1	1
Manufacturer	Unknown	Unknown	Unknown	Ugastove	Iman	Saachi
Fuel Type	Wood	Charcoal & briquettes	Wood	Charcoal & briquettes	LPG Gas	Electricity
Condition of sample	Good	Good	Used	Good	Good	Good
Fuel characteristics	Water content: 7.1% (charcoal), 11.5% (wood), 7.2% (briquettes)					
	Low heating value (LHV): 29.5MJ/kg (charcoal), 17.3MJ/kg (wood), 21.0MJ/kg (briquettes), 46.1MJ/kg (LPG)					
Test environment conditions:	Ambient temperature: 29°C - 32°C Wind speed: controlled wind environment					

Stove description and physical characteristics

Three Stone Stove. Uses Firewood as fuel: Found in Kinoni, Makerere a Kampala Suburb. It is exactly a replica of stone stoves predominantly found in Rural areas in Uganda as per the study findings

Improved Installed household Stove. It uses firewood as fuel: Found in Nansana Town Nansana Municipality in Wakiso District. This stove is commonly referred as Rolena across the country. It varies in size and specifications and this too comes with varied performance. There is no clear standardization of this stove.

Traditional Ceramic mobile stove. It uses both charcoal and briquettes. Found in Gulu central market in Nothern Uganda. This is a replica of traditional stoves predominant in urban households across the country

An improved mobile charcoal/briquettes stove. This was purchased in Soweto market in Masaka town masaka municipality.

An LPG stove with two cooking points. This kind of stove was largely used by urban households who used LPG as fuel for cooking. It was purchased in Wandegeya Market in Kampala Capital City

An electric stove with two cooking points. This was largely utilized in urban households that used electricity for cooking. It was purchased in Soroti Town Soroti District in Eastern Uganda.

Identification of test method

Test equipment:	Weighing scale	Barometer	Moisture meter	Weighing Scale
Serial no/asset no.	CIR/WBT/03	BRM001	CIR/MST/04	CIR/PBS/41

Comparison of time period to cook using the wood as baseline fuel

Wood performance was conducted in two types of stoves (traditional 3 stone and the improved installed wood stove) in comparison with LPG and electricity. An electric hot plate of power rating (1000W) cooked 0.5Kgs of beans using the same cook took 174 minutes which was longer than the Home gas stove (151m), the improved installed wood stove (129m) and even the traditional stone cook stove (153). The cooking tests were done on a cold start implying the extended duration for the hot plate could be attributed to the transfer of electric energy to heat the plates (Rose & Morawicki, 2023). The improved installed wood stove cooked fastest because it losses less energy during cooking and it maximizes the use of every energy produced by the fuel. The test methods outlined, such as using a weighing scale and moisture meter, ensure accurate data collection on fuel consumption and stove performance (Ahiekpor, 2014; Ossei-Bremang et al., 2023). However, there is a need for standardized testing to enable consistent comparisons across stove types. Wood performance was conducted in two types of stoves (traditional 3-stone and the improved installed wood stove) in comparison with LPG and electricity as shown in Table 2. The cooking tests revealed interesting results. An electric hot plate took 174 minutes to cook 0.5 kg of beans, which was significantly longer than the all the stoves. The extended cooking time for the electric hot plate can be attributed to the transfer of electrical energy to heat the plate, especially since the tests were conducted on a cold start (Rose & Morawicki, 2023). The Improved Installed Wood Stove performed the best because it loses less energy during cooking and maximizes the use of the fuel's energy. For future improvements, it is essential to standardize stove designs and develop performance benchmarks for stoves like the Rolena (Njoku et al., 2019; Samal et al., 2022). The study further emphasizes the importance of setting performance benchmarks for stove models like the Rolena and conducting emissions testing to inform policy and guide the adoption of cleaner technologies. While electric and LPG stoves remain critical for sustainable energy transitions, improved biomass stoves continue to offer viable intermediate solutions, particularly in settings where modern fuels remain inaccessible or unaffordable (Adane et al., 2020; Adhikari et al., 2020; KC et al., 2020).

Table 2. Comparison of the fuel performance and cooking time based on different fuels in the chosen stoves.

Comparison of Fuel consumption using Wood as baseline Fuel				
	Type of Stove			
Parameter	**Traditional 3-stone fire**	**Improved installed wood stove**	**Home Gas stove**	**Electric Hot Plate**
Food cooked (kg)	0.5	0.5	0.5	0.5
Cooking time (min)	153	129	151	174
Specific fuel consumption (MJ/kg)	102.438	38.811	13.281	10.420
Percentage difference (%)	-	62.1%	65.8%	73.2%
Comparison of Stoves using charcoal as the Fuel				
	Type of Stove			
Parameter	**Traditional 3-stone fire**	**Improved installed wood stove**	**Home Gas stove**	**Electric Hot Plate**
Food cooked (kg)	0.5	0.5	0.5	0.5
Cooking time (min)	153	129	151	174
Specific fuel consumption (MJ/kg)	102.438	38.811	13.281	10.420
Percentage difference (%)	-	62.1%	65.8%	73.2%
Comparison of Stoves using charcoal as the Fuel				
	Type of stove			
Parameter	**Traditional ceramic stove**	**Ugastove**	**Home Gas stove**	**Electric Hot plate**
Food cooked (kg)	0.5	0.5	0.5	0.5
Cooking time (min)	166	164	151	174
Specific fuel consumption (MJ/kg)	9.183	6.717	13.281	10.420
Percentage difference (%)		26.9%	-97.7%	-55.1%
Comparison of stoves using briquettes as the fuel				
	Type of stove			
Parameter	**Traditional ceramic stove**	**Ugastove**	**Home Gas stove**	**Electric Hot plate**
Food cooked (kg)	0.5	0.5	0.5	0.5
Cooking time (min)	156	170	151	174
Specific fuel consumption (MJ/kg)	5.182	3.751	13.281	10.420
Percentage difference (%)		27.6%	-254.0%	-177.8%

Comparison of fuel consumption using wood as baseline fuel

In comparing the fuel consumed by wood stoves to cook the same 500gm meal of beans with LPG and electric stoves, the traditional 3 stove consumed the highest amount of fuel 102.44MJ/28.46KWh; the improved installed wood stove 38.81MJ/10.78KWh; home gas stove 13.28MJ/3.69KWh; and electric hot plate 10.42MJ 2.89KWh Table 2. In comparison for wood as a stove in the three stone cook stove with other improved stove, the electric hot plate is 73.2% more efficient in terms of cooking duration and fuel consumed. The LPG and the home gas performed equally better than the three stone stove with a percentage difference of 65.8% and 62.1 % respectively (Osano *et al*., 2020). When looking at cooking time and fuel efficiency, the Electric Hot Plate proved to be 73.2% more efficient than the traditional 3-stone stove (Table 2). In comparison, the LPG stove showed a 65.8% improvement, and the Home Gas Stove was 62.1% more efficient in both fuel consumption and cooking time (Samal *et al*., 2022; A. Tesfay *et al*., 2024). These results shown in Table 2 underscore the substantial benefits of switching to modern stoves, which can save fuel, reduce emissions, and improve cooking speed, offering both environmental and practical advantages for households (Osano *et al*., 2020). In comparing fuel consumption for cooking the same 500 g meal of beans, the traditional three-stone stove was found to be the least efficient, consuming 102.44 MJ (28.46 kWh) of energy. In contrast, the Improved Installed Wood Stove demonstrated markedly better performance, requiring only 38.81 MJ (10.78 kWh)—a 62% reduction in energy use. Modern energy systems performed even more efficiently: Home Gas Stove used 13.28 MJ (3.69 kWh), while the Electric Hot Plate consumed 10.42 MJ (2.89 kWh), making it the most energy-efficient of all tested stoves. When comparing both fuel consumption and cooking time, the Electric Hot Plate was 73.2% more efficient than the traditional three-stone stove. The LPG stove and Home Gas Stove were 65.8% and 62.1% more efficient, respectively (Afrane *et al*., 2022; Ossei-Bremang *et al*., 2023). These results (Table 2) highlight the clear advantages of transitioning to modern stoves, not only in terms of fuel savings but also in reducing emissions and improving cooking speed. The data strongly support the case for accelerating the adoption of clean cooking technologies as a means of achieving energy efficiency, environmental protection, and improved public health (Adane *et al*., 2020).

Comparison of time period to cook using charcoal as baseline fuel

Charcoal performance was conducted in two types of stoves; traditional ceramic stove in comparison with the Uga-stove, LPG and electricity stoves; an electric hot plate of power rating (1000W) cooked 0.5Kgs of beans using the same cook took 174m minutes which was longer than the Home gas stove (151m), the Uga-Stove (164m) and even the traditional ceramic stove (166m). Generally, it was observed that charcoal stoves (163.75m) cooked the same meals longer than wood stoves (151.75m) which could be because it is easy to ignite and combust dry wood as compared to charcoal (Table 2). Notably, the Uga-Stove, an improved charcoal stove design, performed better than the traditional ceramic stove, suggesting that stove design still plays a critical role in fuel efficiency and cooking time. However, both charcoal stoves lagged behind the LPG and electric options in performance (Bailis *et al*., 2021; Woolley *et al*., 2022). These findings highlight the need for continued investment in cleaner and more efficient cooking solutions. While charcoal remains a dominant cooking fuel in urban households, its relative inefficiency when compared to modern fuels suggests a need for transition strategies toward LPG, electricity, or other clean energy alternatives, especially in the context of Uganda's energy and environmental sustainability goals.

Comparison of fuel consumption using charcoal as baseline fuel

In comparing the fuel consumed by charcoal stoves to cook the same 500gm meal of beans with LPG and electric stoves, the UgaStove improved stove consumed the least amount of fuel 6.717MJ/1.87KWh; traditional ceramic stove 9.183MJ/2.55KWh; electric hot plate 10.42MJ 2.89KWh and the home gas stove consumed the most at 13.28MJ/3.69KWh (Table 2). In comparison for charcoal as a stove in the traditional ceramic stove with other improved stove, the UgaStove brand showed a 26.9% percentage difference whereas the electric hot plate is (-55.1%) and the home gas stove using LPG at (-97.7%) in term of cooking duration and fuel consumed. When comparing the fuel consumed to cook the same 500g meal of beans across different stoves, the UgaStove, an improved charcoal stove, was the most fuel-efficient, using only 6.717MJ (1.87KWh). The Traditional Ceramic Stove followed with 9.183MJ (2.55KWh), while the Electric Hot Plate used 10.42MJ (2.89KWh), and the Home Gas Stove had the highest consumption at 13.28MJ (3.69KWh) (Woolley *et al*., 2022). These results highlight that while improved charcoal stoves like the UgaStove offer significant fuel savings compared to traditional designs, modern energy sources such as electricity and LPG may consume more fuel energy in practice, possibly due to heat transfer inefficiencies or variations in cooking dynamics. Nonetheless, modern stoves still offer benefits in terms of cleaner combustion and reduced indoor air pollution (Kaur & Pandey, 2021; Owusu-Amankwah *et al*., 2023).

Comparison of time period to cook using briquettes as baseline fuel

Briquettes performance was conducted in two types of stoves, traditional ceramic stove in comparison with the Uga-stove, LPG and electricity stoves; an electric hot plate of power rating (1000W) cooked 0.5Kgs of beans using the same cook took 174 minutes which was longer than the Home gas stove (151m), the Uga-Stove (170m) and even the traditional ceramic stove (156m) (Table 2). Generally, it was observed that briquettes stoves (162.75m) cooked the same meals longer than charcoal (163.75m) and wood stoves (151.75m) which could be because it takes longer to ignite and combust as compared to charcoal and wood stoves (Li *et al*., 2022). Briquette performance was assessed using two common stove types: the Traditional Ceramic Stove and the Uga-Stove, and compared with LPG and electric stoves (Obi *et al*., 2022). When cooking 0.5 kg of beans, the electric hot plate (1000W) had the longest cooking time at 174 minutes, followed by the Uga-Stove at 170 minutes, the traditional ceramic stove at 156 minutes, and the home gas stove at 151 minutes (Ajimotokan *et al*., 2019). On average, briquette stoves took 162.75 minutes to cook the same meal slightly longer than charcoal stoves at 163.75 minutes and wood stoves at 151.75 minutes (Table 3). These findings suggest that while briquettes are a viable alternative fuel especially from a sustainability standpoint improvements in stove design and briquette quality are needed to enhance their practical efficiency for everyday cooking in Uganda (Mainimo *et al*., 2022; Mwamlima *et al*., 2023; Oteu *et al*., 2024).

Comparison of fuel consumption using briquettes as baseline fuel

In comparing the fuel consumed by briquette stoves to cook the same 500gm meal of beans with LPG and electric stoves, the UgaStove improved stove consumed the least amount of fuel 3.751 MJ/1.04KWh; traditional ceramic stove 5.182 MJ/1.44KWh; electric hot plate 10.42MJ 2.89KWh and the home gas stove consumed the most at 13.28MJ/3.69KWh. In comparison for charcoal as a stove in the traditional ceramic stove with other improved stove, the UgaStove brand showed a 27.6% percentage difference whereas the electric hot plate is (-177.8%) and the home gas stove using LPG at (-254%) in term of cooking duration and fuel consumed. When comparing the UgaStove's performance against other stoves, it showed a 27.6% improvement over the traditional ceramic stove in terms of both cooking time and fuel consumption. In contrast, the electric hot plate consumed 177.8% more energy, and the LPG stove used 254% more energy, relative to the UgaStove under the same cooking conditions. These results underscore the energy-saving potential of improved briquette stoves like UgaStove, particularly in contexts where affordability, fuel accessibility, and reduced emissions are priorities (Skreiberg *et al*., 2023).

Table 3. Comparison of the costs of different fuels in selected stoves.

Comparison of costs using wood as a baseline fuel			
Stove type	**Quantity of fuel used for the meal (Kg) /(KWh)**	**Cost of fuel per unit (Ugx)**	**Cost per meal**
Traditional 3-stone fire	12.804	400	5,121.6
Installed mud stove	4.852	400	1,940.8
Home Gas stove	0.56	9833 (12Kg cylinder upper limit for most HH)	5,506.5
Electric Hot Plate	5.788 KWh	759	4,393.1
Comparison of costs using charcoal as a baseline fuel			
Stove type	**Quantity of fuel used for the meal (Kg) /(KWh)**	**Cost of fuel per unit (Ugx)**	**Cost of fuel per unit**
Traditional ceramic Stove	0.634	1000	634.0
UgaStove	0.464	1000	464.0
Home Gas stove	0.56	9833 (12Kg cylinder upper limit for most HH)	5,506.5
Electric Hot Plate	5.788 KWh	759	4,393.1
Comparison of costs using briquettes as a baseline fuel			
Stove type	**Quantity of fuel used for the meal (Kg) /(KWh)**	**Cost of fuel per unit (Ugx)**	**Cost of fuel per unit**
Traditional ceramic Stove	0.416	1000	416.0
UgaStove	0.302	1000	302.0
Home Gas stove	0.56	9833 (12Kg cylinder upper limit for most HH)	5,506.5
Electric Hot Plate	5.788 KWh	759	4,393.1

Comparison of costs using wood as a baseline fuel

Key to the question of adoption is the cost of the fuel which greatly influences the choice of any improved and traditional devices to be adopted by a household. The amount of energy required to prepare 1Kg of the NABE 1 variety locally known as "masavu" was on average 12.8Kg when using the traditional 3-stone fire, 4.9Kg for the Installed mud stove, 0.56Kg for the Home Gas stove (LPG), and 5.8units when using an electric hot plate. The cost of boiling and frying a Kg of beans while using electricity was Ugx 4,393.1/= cooked on an electric hot plate of 1000W power rating; which remains high for most rural and urban households in comparison to the available options (Table 4). Wood fuel combusted in the Installed mud stove ranked was the cheapest at Ugx 1,940.8/=; in comparison to the LPG at Ugx5, 506.5/=. It can generally be concluded that cooking with wood fuel an improved installed wood stove like an installed mud stove is cheaper than cooking with a traditional 3 stone stoves (Ugx 5,121.6/=), LPG (Ugx 5,506/=) and an electric hot plate (Ugx4,393.1/=). The findings highlight the significant role that fuel cost plays in household decision-making regarding stove adoption, especially in low- and middle-income settings. Despite the environmental and health benefits of modern cooking technologies such as LPG and electric stoves, their high operational costs remain a major barrier to widespread adoption. These results suggest that promoting improved biomass stoves, alongside targeted subsidies or tariff adjustments for cleaner energy sources, could provide a pragmatic transition pathway for many Ugandan households, bridging the affordability gap while reducing emissions and improving energy access (Ray & Smith, 2021).

Table 4. Cost and effort analysis of improved cooking technologies.

Improved Technology	Capital Investment	Maintenance/ Operational Costs	Money Costs of acquiring Fuel	Time and Learning Costs
Household				
Improved Installed Household Wood Stove (IHWS)	High: Costs on average 200,000 to install the (IHWS)	Moderate: Requires regular maintenance bi-annually or annually depending on the user	Low: Cost of acquiring wood is low, can be purchased in small quantities and is available	Very Low: Functionality is as simple as traditional stoves already known
Mobile improved charcoal Stove (size 1,2 &3)	Moderate cost: Size 2 which is most common ranges between 20,000 to 50,000 depending on the market	Have no maintenance costs	Low: Cost of acquiring charcoal is low, can be purchased in small quantities and is available	Very Low: Functionality is as simple as traditional stoves already known
LPG Stove	High: The cost of LPG Cylinder and Stove is high, ranges between 200,000 to 500,000 Uganda shillings	Has no maintenance costs	High: The cost of refilling a gas cylinder is high. Ranges between 50 to 200,000	High: Especially given the fact that the public perceive it to have a danger of burning the house
Electric Stove	Moderate: the cost of purchasing an electric stove/hot plate is moderate. Depends on size and functionality. Can get as low as 30,000 and can get as high as 2,000,000.	Moderate: To repair the switches, fuses, plugs, thermostat etc.	Very High: The cost of installing electricity is very high for new users switching to it. However, those already installed the cost of purchasing power units is very low since any money can purchase units	High: Especially given the fact that the public perceive it to be dangerous
Institutions				
Improved Installed institutional wood stove	Moderate: Institutions that have their business depend on cooking (hotels, schools and bakeries) consider the cost as moderate. It costs between 500,000 to 5,000,000 depending on size and materials used	Moderate: Requires regular maintenance bi-annually or annually depending on the user	Low: Cost of acquiring wood is low, can be purchased in small quantities and is available	Very Low: Functionality is as simple as traditional stoves already known
Mobile Improved Charcoal stoves (size 4 to 8)	Low: Size 5 which is most common (in hotels & schools) costs between 200,000 to 500,000 depending on the market	Have no maintenance costs	Low: Cost of acquiring charcoal is low, can be purchased in small quantities and is available	Very Low: Functionality is as simple as traditional stoves already known
Institutional LPG Stove	High: The cost of LPG Cylinder and Stove is high ranges between 500,000 to 10,000,000 Uganda shillings	Have no maintenance costs	The cost of refilling a gas cylinder is high.	High: Especially given the fact that the public perceive it to have a danger of burning the house
Institutional Electric Stove	High: Moderate: the cost of purchasing an institutional electric stove is high.	Moderate: To repair the switches, fuses, plugs, thermostat etc.	High: The cost of installing electricity is very high for new users switching to it. However, those already installed the cost of purchasing power units is very low since any money can purchase units	High: Requires training to use the stove.

[1]Costs between 50,00 to 100,000 for labor and expertise and average of 50,000 to 100,000 for materials i.e. mud, bricks, stones and cement; [2]For instance, smart home costs 30,000 and Ugastove costs 25,000 in Major outlet towns in Uganda. However, in Wandegeya and Nakasero Markets the same stoves cost 45,000 Uganda shillings; [3]A 13 kg cylinder (Oryx) with LPG costs 300,000 Uganda shillings at retail price. The stove costs with two cooking points (muni brand) costs 150,000 Uganda shillings; [4]The cost of refilling a 13 kg cylinder for total is 118000 at retail outlets; [5]A two cooking pot electric stove of a Philips brand costs 160,000 Uganda shillings in an electric appliances shop in Mbarara town; [6]It costs 1000,000 in labour and expertise and approximately 1,500,000 in materials to build a medium 4 cook pots in a school.

Comparison of costs using charcoal as a baseline fuel

The results were different when using charcoal in the traditional ceramic stove in comparison to the improved charcoal stove (UgaStove); LPG and electric hot plate**.** The amount of charcoal required to prepare 1Kg of Beans was on average 0.634 Kg when using the traditional ceramic stove, 0.464Kg for the improved charcoal stove (UgaStove), 0.56Kg for the Home Gas stove (LPG), and 5.8units when using an electric hot plate which remains high for most rural and urban households in comparison to the available options (Table 4). The cost of boiling and frying a Kg of masavu beans while using electricity was Ugx 4,393.1/=, cooked on an electric hot plate of 1000W power rating, Charcoal was the cheapest at Ugx 464/=; in comparison to the LPG at Ugx5, 506.5/= (Table 4). These results reaffirm the importance of stove efficiency in reducing fuel costs, particularly for charcoal users in both urban and peri-urban areas. The improved charcoal stove (UgaStove) consistently outperformed the traditional ceramic stove, demonstrating not only reduced fuel consumption but also significant cost savings per meal. While LPG and electric cooking offer cleaner alternatives, their comparatively higher energy costs continue to deter adoption among lower-income households. The affordability of the UgaStove makes it a practical and scalable solution for communities still reliant on charcoal, providing an intermediate step toward cleaner energy without placing additional financial burden on users. This underscores the need to prioritize improved biomass technologies in energy access programs while addressing the long-term affordability of modern fuels (Ossei-Bremang *et al*., 2023).

Comparison of costs using briquettes as a baseline fuel

The results were different when using briquettes in the traditional ceramic stove in comparison to the improved charcoal stove like (UgaStove); LPG and electric hot plate. The amount of briquettes required to prepare 1Kg of beans was on average 0.416 Kg when using the traditional ceramic stove, 0.302 Kg for the improved charcoal stove (UgaStove), 0.56Kg for the Home Gas stove (LPG), and 5.8units when using an electric hot plate. The cost of boiling and frying a Kg of beans while using electricity was Ugx 4,393.1/= cooked on an electric hot plate of 1000W power rating which remains high for most rural and urban households in comparison to the available options. Briquettes combusted in the Improved mobile charcoal stove ranked was the cheapest at Ugx 302/= for 1Kg of beans; in comparison to the LPG at Ugx5, 506.5/= as shown I Table 3 (Woolley *et al*., 2022). It can generally be concluded that cooking with briquettes as a fuel in an improved mobile charcoal stove like a Uga-Stove is cheaper than cooking with a traditional ceramic one stove (Ugx 416/=), LPG (Ugx 5,506/=) and an electric hot plate (Ugx4,393.1/=). The findings clearly demonstrate that briquettes, when used in an improved charcoal stove like the UgaStove, offer a highly cost-effective cooking solution. The improved stove required significantly less fuel than the traditional ceramic option, reflecting better combustion efficiency and heat retention. In cost terms, cooking with briquettes in the UgaStove proved to be the most affordable option among all tested fuels and technologies. While LPG and electricity remain cleaner alternatives, their higher operational costs particularly for electricity render them less accessible to the average household. These results reinforce the potential of briquettes as a low -cost, sustainable fuel, especially when paired with efficient stove technologies. Promoting such combinations can provide a viable bridge toward cleaner cooking without excluding low-income users due to cost barriers (Ajimotokan *et al*., 2019; Arachchige, 2021; Mwamlima *et al*., 2023; Oteu *et al*., 2024).

Techno-economic analysis

Ranking from top-bottom is cheapest to most expensive fuel in a specific device

From this analysis, Briquettes (*made from biomass material specifically kitchen wastes and plant materials: cassava*) is the cheapest option followed by Charcoal. It is important to note that briquettes did not pass the test for availability and accessibility and thus did not find its way into our recommendations (Figure 1). Though efforts to make it available are commendable, the survey of the briquettes suppliers revealed a low capacity and number to avail the briquettes in all the fuel outlets in the country. However, supporting the suppliers to build this capacity would be a good move towards availing this cleaner energy to the households and institutions (Figure 1). Although briquettes emerged as the cheapest fuel option in the analysis outperforming charcoal, LPG, and electricity in terms of cost per kilogram of food cooked their limited availability and accessibility hinder widespread adoption. Made from biomass materials such as kitchen waste and cassava residues, briquettes offer a clean and affordable alternative, especially when used in improved stoves like the UgaStove. However, the survey of suppliers revealed a low production capacity and limited distribution, with most briquette vendors unable to meet demand across fuel outlets nationwide. As such, despite their cost advantage, briquettes were excluded from the final recommendations due to practical limitations in market presence (Figure 1). Nevertheless, investing in supply chain development and supporting local producers to scale operations could significantly enhance briquette availability, paving the way for broader adoption of this cleaner energy source among households and institutions (Kaoma & Gheewala, 2021; Nsamba *et al*., 2021).

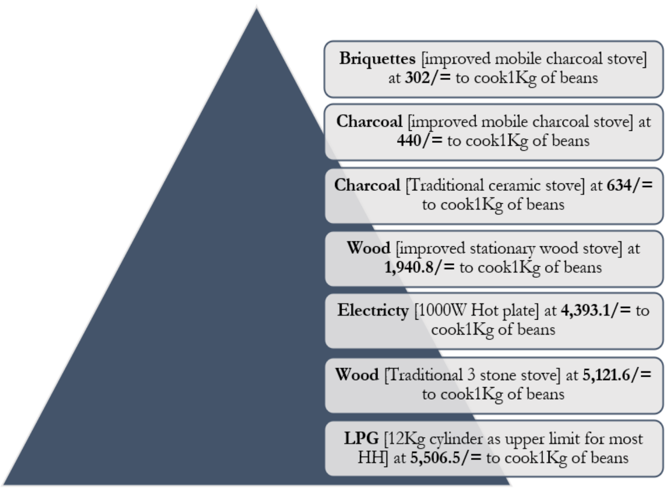

Figure 1. *Ranking from top-bottom is cheapest to most expensive fuel in a specific device.*

Benefits associated with clean fuels and improved technologies

Reduced carbon emissions and associated health benefits

According to Climate and Clean Air Coalition 2020, in 2016 2.6 million people in the developing world died prematurely from exposure to kitchen air pollution. Additionally, each year tens of millions are sickened, injured or burned as a result of using biomass as fuel with traditional devices. This study discovered that households and large institutions are aware of this danger but continue to use the same due to social, economic and technical factors. Already there is positive shift towards a better direction as adoption starts with awareness (Figure 1). Supporting players in the sector to avail clean fuels conveniently will increase the chances of many institutions and households escaping the dangers of using traditional stoves and biomass fuels. According to the Climate and Clean Air Coalition (2020), an estimated 2.6 million people in the developing world died prematurely in 2016 due to exposure to household air pollution, primarily from cooking with biomass on traditional stoves. In addition, tens of millions suffer annually from burns, respiratory illnesses, and other health complications linked to unsafe cooking practices. While this study revealed that most households and institutions are aware of the health risks, many continue to use traditional stoves due to social, economic, and technical constraints. However, the findings also point to a positive shift, with increasing awareness serving as the initial step toward broader adoption of clean cooking technologies (Figure 1). Strengthening support to key players in the clean cooking sector especially in making clean fuels more accessible and convenient can greatly accelerate this transition and help reduce the health burden associated with traditional biomass use (Arora *et al*., 2014; Kim & Boehman, 2021; Manaye *et al*., 2022).

Improved forest cover and associated climate benefits

Forests are central to SDG 15 and contribute to achievement of SDG 7 targets. The adoption of clean fuels and improved efficient stoves will greatly contribute to the improved forest cover and the associated ecosystem benefits. To conclude this chapter, the adoption of clean fuels and technologies has both economic and social benefits. The economic benefits are two; 1) fuel saving (2) time saving. The social benefits are also broadly grouped into two 1) improved forest ecosystems and (2) reduced carbon emissions. Marketing and communication messages that promote adoption of clean fuels and improved technologies should focus on marketing these benefits (Figure 1). Forests play a central role in achieving Sustainable Development Goal (SDG) 15 on life on land and directly contribute to the realization of SDG 7, which promotes access to affordable, reliable, and sustainable energy. The adoption of clean fuels and improved energy-efficient stoves is therefore critical—not only for protecting and restoring forest cover but also for delivering broader ecosystem services such as biodiversity conservation, water regulation, and climate stability. The transition to clean cooking technologies presents both economic and social benefits. The economic gains are primarily through fuel savings and time efficiency, reducing the burden on household resources and freeing up time for other productive activities. On the social front, the benefits include enhanced forest ecosystem health and reduced greenhouse gas emissions, contributing to local resilience and global climate goals. To accelerate adoption, marketing and communication strategies must emphasize these tangible benefits—fuel and time savings, healthier forests, and a cleaner atmosphere—to make the case more compelling to both households and institutions (Anenberg *et al*., 2017; Rosenthal *et al*., 2018; Khavari *et al*., 2023).

Analysis of switching costs to cleaner fuels and improved technologies

In order to analyze the likelihood of institutions and households switching from traditional to improved cooking technologies, the study conducted an analysis based on the identified switching costs. The switching costs identified include; Capital investment to acquire a new device or ventilation system, maintenance and operational costs, money costs of acquiring the fuel, learning costs of using the new technology, and time costs incurred while preparing and acquiring the new device. This is against the benefits of time saving, health benefits, fuel Saving, improved forest ecosystems and reduced carbon emissions. To evaluate the likelihood of institutions and households transitioning from traditional to improved cooking technologies, the study analyzed the impact of various switching costs against the expected benefits. The key switching costs identified include the initial capital investment required to purchase a new stove or ventilation system, ongoing maintenance and operational expenses, cost of acquiring cleaner fuels, learning costs associated with adopting unfamiliar technology, and the time required to acquire and adapt to new devices. These costs were weighed against the significant and well-documented benefits of improved cooking technologies, which include: time savings, health improvements, reduced fuel consumption, protection of forest ecosystems, and lower carbon emissions. The analysis suggests that while switching costs can present substantial barriers, especially for low-income users, the long-term socio-economic and environmental benefits outweigh the initial costs, making a strong case for targeted support mechanisms to ease the transition. These may include subsidies, financing schemes, training, and awareness campaigns to address both financial and behavioral constraints.

Conclusion

This study confirms that increased access to affordable and efficient cooking technologies significantly reduces biomass fuel consumption in institutions, leading to potential declines in deforestation. The analysis revealed that institutions with access to energy-saving technologies were six times more likely to reduce wood fuel use ($p = 0.000$), while those that found these technologies affordable were 4.3 times more likely to adopt them ($p = 0.021$). Furthermore, institutions that had adopted any clean energy-saving solution reported a 23.7% reduction in wood fuel expenditure, a direct economic incentive for broader adoption. These findings underscore the urgent need to scale up clean cooking solutions in line with Uganda's Vision 2040 and NDP IV, which emphasize improving energy efficiency, regulating energy audits, and establishing energy conservation funds. Regionally, the study supports the EAC Energy Strategy, which aims to cut biomass use by 50%, a target that requires actionable data on fuel use patterns and viable alternatives. Globally, this research contributes to the goals of the Paris Agreement by demonstrating a feasible pathway to reduce emissions from biomass use and supports SDG 7, which calls for "affordable, reliable, sustainable, and modern energy for all" by 2030. By linking evidence with policy goals, the study offers a compelling case for accelerating the transition to sustainable energy use in institutions across Uganda and similar contexts.

DECLARATIONS

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