

Clean cooking transition in Ghana: Challenges, opportunities, and strategic pathways for sustainable development

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ABSTRACT

This study evaluated the challenges and opportunities for clean household cooking transition in Ghana, aligning with Sustainable Development Goals of health, affordable clean energy and climate action. Through a mixed-methods approach integrating national statistics, policy analysis, and case studies, spatial and socioeconomic disparities in clean cooking access were evaluated to assess the role of cultural, financial, and infrastructural barriers. The findings show that despite government efforts like the Gyapa Improved Cookstove project and National Liquefied Petroleum Gas (LPG) Program, only 31 % of Ghanaians have access to clean cooking. Affordability remains a challenge to clean cooking as low-income households spend 3.1 % of their income on LPG compared to 0.7 % on wood. Other barriers include fragmented supply chains, limited access to modern fuels, inadequate infrastructure, and sociocultural preferences. Regional disparities persist, with northern Ghana's average household income (USD 1287 - 2276) limiting access to modern fuels compared to southern regions (USD 2144 - 6425). Successful models from Rwanda (Inyenyeri pellet cookstoves) and Kenya (pay-as-you-go LPG) projects highlight scalable solutions. Context-specific strategies are proposed to accelerate clean cooking transition. These strategies include scaling financial mechanisms such as carbon credit programs and rental or leasing schemes to reduce the cost of clean cooking, establishing local manufacturing firms, and behavioral initiatives addressing cookstove stacking practices and driving long-term adoption of clean cooking technologies. Energy policy revisions and regulatory frameworks must prioritize renewable energy integration for off-grid communities and strengthen the monitoring of policies, including Ghana's Renewable Energy Master Plan. By addressing these challenges and leveraging emerging opportunities, Ghana can reduce household air pollution, mitigate deforestation, and ensure equitable clean cooking access to advance the United Nations Sustainable Development Goals. This study provides actionable insights and strategies for policymakers and stakeholders to accelerate clean cooking transitions, emphasizing the need for holistic, collaborative governance, financing innovation, and culturally tailored interventions.

Introduction

About 2.1 billion people rely heavily on traditional solid biomass fuels (SBFs) such as wood and charcoal for household cooking (IEA et al., 2024), which is the leading cause of severe household air pollution (HAP) and environmental degradation. HAP contributes significantly to adverse health impacts, including respiratory diseases, particularly among women and children, and is responsible for 2.3 million premature deaths annually (Bennitt et al., 2021). In sub-Saharan Africa, where ~85 % of the population depends on SBFs, the health risks associated

with HAP is particularly severe (IEA, 2023). The United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), highlight the importance of reducing household air pollution, as clean cooking solutions can significantly mitigate the health risks linked to respiratory diseases (Carlsen & Bruggemann, 2022). Aside from that, the UN SDGs emphasize universal access to clean and affordable energy (SDG 7) and climate action (SDG 13). However, progress remains limited due to socioeconomic, cultural, and infrastructural barriers impacting adoption (Addo & Olajide, 2021; Boude-wijns et al., 2022).

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In Ghana, the situation reflects the global crisis. About 75 % of Ghanaians (~26 million), mostly in rural and low-income urban areas, use SBFs for cooking, with 31.1 % and 23.3 % of households using wood and charcoal, respectively (GSS, 2021b; Tawiah et al., 2022). HAP from cooking is linked to the premature death of 18,000 people every year, primarily women and children below 4 years who spend the most time near the cooking area (Addo & Olajide, 2021; Nuhu et al., 2022). However, HAP will remain a challenge in Ghana since household demand for SBFs is projected to grow with population, comprising 23 % of total energy demand by 2030 (Kemausuor et al., 2015). Apart from that, cooking with SBFs accounts for the 60 % reduction in forest cover in Ghana (Asamoah et al., 2020). With one of the highest global yearly deforestation rates (2 %), this observation could destroy Ghana's forests by 2050 if not mitigated (Acheampong et al., 2019). Aside from these health and environmental concerns, the economic burden of cooking fuel costs is evident among Ghanaian households and disproportionately affects low-income households (Owusu-Amankwah et al., 2023). To show its commitment to advancing these SDGs, the government of Ghana has strived to improve access to clean cooking solutions (Adams et al., 2023). Key interventions include the National Liquefied Petroleum Gas (LPG) Program for rural areas, the distribution of 200,000 Gyapa charcoal stoves, and policies promoting biomass pellets and gasifier cookstoves, as outlined in Ghana's Renewable Energy Master Plan (Mawusi et al., 2023a).

However, adoption rates remain low due to affordability constraints, fragmented distribution networks, housing and social factors, and strict adherence to culturally preferred cooking methods (Adams et al., 2023; Nuhu et al., 2022; Owusu-Amankwah et al., 2023). Only 31 % of Ghanaian households use clean cooking fuels (e.g., LPG, biogas, improved cookstoves), far below the target of the country's action plan for clean cooking target of 50 % national penetration by 2015 with a glaring rural-urban disparity (GEC, 2022c). Globally, efforts like Rwanda's Inyenyeri pellet stove program and China's biomass energy policies highlight the role of clean cooking in advancing SDG 7 (affordable energy) and SDG 13 (climate action) (Farabi-Asl et al., 2019; Jagger & Das, 2018; Li et al., 2022; Shrestha, 2021). These examples reinforce the urgency of addressing Ghana's unique socioeconomic barriers to replicate such successes. Promoting clean cooking in Ghana is crucial not only for achieving SDGs 7 and 13, but also for improving public health outcomes, especially for vulnerable groups such as women and children (Addo & Olajide, 2021). Given the challenges of traditional cookstoves, innovative solutions are needed for clean cooking in Ghana. Promoting clean cooking in Ghana requires understanding cookstove prevalence, causes of cookstove-related issues, and pathways for sustainable change. Existing studies in Ghana have predominantly focused on technical innovations in cookstove design (e.g., emissions reductions and efficiency), often overlooking the socioeconomic and cultural dynamics that impact user behavior (Guta et al., 2022; Shankar et al., 2020). For instance, Dickinson et al. (2015) and Bawakyillenuo et al. (2021b) stress improving cookstove efficiency but do not explicitly explain the prevalence of stove stacking or why households remain adamant about abandoning traditional SBFs.

This study fills these critical gaps by examining how socioeconomic disparities, cultural practices, and policy frameworks interact to shape the clean cooking landscape in Ghana. Unlike previous technical studies, we integrate national energy statistics and policy analysis to provide a holistic understanding of barriers and opportunities. Specifically, the research aims to 1) quantify the spatial and socioeconomic distribution of clean cooking access among rural and low-income urban households in Ghana; 2) evaluate the role of cultural preferences and affordability in sustaining the use of SBFs, and 3) propose context-specific strategies to align policy interventions with local realities. By highlighting the dual problem of technical solutions and adoption, our study offers evidence-based recommendations and actionable strategies to buoy Ghana's clean cooking transition, advancing SDG 7 and 13 and providing a model for similar contexts in sub-Saharan Africa.

Methodology

Study area

Ghana is a lower-middle-income West African country with a population of 30.8 million (2021 estimate) (GSS, 2021a). It is characterized by a youthful demographic (38 % under 15 years) and 56 % and 44 % live in rural and urban areas, respectively (GEC, 2022c; GSS, 2021b). Ghana is socio-culturally diverse with over 50 ethnic groups, including the Akan, Mole-Dagbon, and Ewe, each with distinct culinary traditions that favor biomass-based cooking methods (e.g., open-fire cooking for dishes like banku and fufu) (GSS, 2019, 2021b). Households often prioritize taste and communal practices, with an average household size of 3.6, amplifying cooking fuel demand, especially in the Northern regions (GSS, 2021b). The average annual household income in Ghana is USD 3342, with the Northern regions earning lower (USD 1287–2276), thus the preference for traditional SBFs (Bawakyillenuo et al., 2021b; GSS, 2019). About 86.3 % of Ghanaians have electricity access, yet unreliable supply and high LPG costs hinder clean cooking transitions (GSS, 2021b).

Literature search

A thorough literature review was conducted using electronic databases such as Google Scholar (<https://scholar.google.com/>), Web of Science (<https://www.webofscience.com/>), and Scopus (<https://www.scopus.com/>) to find relevant publications. These platforms were selected for their multidisciplinary and comprehensive coverage of peer-reviewed academic literature, advanced search functionalities, and robust citation tracking, ensuring access to high-impact studies relevant to energy transitions and clean cooking. The focus was on clean cooking transition in Ghana and its improvement. Keywords included "Ghana", "renewable energy", "environment", "clean cooking", "clean energy transition", "carbon credit programs", "health impacts", "biomass fuels", "climate", "household air pollution", "policy", "sustainable development", "traditional cookstoves" and "sustainability". The search strategy employed Boolean operators to combine keywords into structured search strings, including: "Ghana" AND "clean cooking" AND "sustainable development" OR "energy policy", "household air pollution" AND "clean cooking transition" AND "Ghana", "biomass fuels" OR "traditional cookstoves" AND "health impacts" AND "Ghana". Other variations incorporated terms like "behavioral change," "carbon credit programs," and "renewable energy".

Additionally, institutional reports from the International Energy Agency (IEA; <https://www.iea.org/>), United Nations (UN; <https://www.un.org/>), World Health Organization (WHO; <https://www.who.int/>), Clean Cooking Alliance (CCA; <https://cleancooking.org/>), Ghana Statistical Service (GSS; <https://statsghana.gov.gh/>), Ghana Energy Commission (GEC; <https://energycom.gov.gh/index.php>), Ghana Alliance for Clean Cookstoves and Fuels (GHACCO; <https://www.ghacco.org/>), and other Ghanaian government establishments were also reviewed to incorporate policy documents and national energy statistics. These sources provide critical gray literature and contextual data essential for understanding Ghana's clean cooking landscape. Case studies and technical reports from non-governmental organizations (NGOs) and clean energy initiatives were accessed via their official websites to complement academic findings. All institutional reports and gray literature sources are fully cited in the references section. Furthermore, informal consultations and discussions with relevant stakeholders such as experts from the Ghana Energy Commission, Kwame Nkrumah University of Science and Technology provided access to unpublished information. Our analysis focused on traditional (wood, charcoal and crop residues), clean (biomass pellets, liquefied petroleum gas (LPG), electricity, biogas) cooking fuels which are already included in Ghana's household energy mix.

Household cooking fuels

Available household cooking fuels and consumption

The primary household cooking fuels are wood, charcoal, and LPG, with biogas, electricity, kerosene, crop residue, and others (biomass briquettes, wood pellets, methanol, and solar) also in use (Bawakyillenuo et al., 2021b). Fig. 1 details the percentage distribution of household cooking fuel types in Ghana, highlighting the dominance of wood and charcoal in rural areas (62 % and 16 %, respectively) compared to urban areas (11 % and 28 %). Further details on the regional distribution are shown in supporting information (SI) Section S2. While traditional solid biomass fuels (SBFs) such as firewood and charcoal remain dominant, cleaner alternatives offer significant environmental and health benefits. Table 1 summarizes key clean cooking technologies, fuel sources, and their comparative advantages over SBFs. In 2021, the residential sector consumed 1542 and 1113 ktoe of wood and charcoal, respectively (GEC, 2022a; Mawusi et al., 2023b). Each household in Ghana consumes about 2.8 tons of wood annually (Mawusi et al., 2023a). Overall biomass consumption decreased from 3432 ktoe in 2000 to 3162 ktoe in 2021, with households being primary users (84 % in 2021) (Section S3). The industrial and service sectors also accounted for 12.2 % and 3.8 %, respectively (GEC, 2021, 2022a).

Currently, LPG is the most popular cooking fuel in Ghana, especially in urban areas, and is steadily increasing in rural areas (Fig. 1). In 2021, household cooking with LPG reached 252 ktoe, accounting for 68 % of the total LPG used in Ghana (GEC, 2022a). The popularity of LPG in households is due to increased fuel access and demonstration programs in rural areas (Kar et al., 2024). This observation corroborates the gradual uptake of clean cooking in Ghana, although at a modest pace (Nuhu et al., 2022). However, electric cooking is not popular, as is only used by 0.39 % of households (Fig. 1). Household LPG demand is expected to rise by 67 % by 2030, and electricity demand per household is projected to increase by 58 % due to more significant appliance usage (GEC, 2019b).

Also, the choice of household cooking fuel is influenced by geography (Fig. S2). Wood and crop residues are widespread in the northern regions, while charcoal and LPG dominate in southern coastal areas. The disparity influences this observation in annual household incomes

across the regions: USD 1287–2276 vs. USD 2144–6425 (Mawusi et al., 2023b). Low-income households typically prefer cooking with SBFs in traditional stoves than their high-income counterparts (Guta et al., 2022). In regions with high household wood consumption, the usage decreases in the following order: Ashanti > Eastern > Northern > Central > Western. For charcoal usage, the trend is as follows: Western < Eastern < Central < Greater Accra < Ashanti. Household cooking with LPG increases in the order Volta < Western < Eastern < Central < Greater Accra.

Projections indicate a decline in household wood demand from 2272 ktoe to 2070 ktoe by 2030 and increased charcoal demand from 832 ktoe in 2020 to 971 ktoe by 2030 (GEC, 2019b). Despite the forecasted decrease in wood demand, the increase in charcoal use signals an environmental burden to Ghana due to its associated rise in deforestation and carbon emissions levels (Azasi et al., 2020). This observation highlights the reliance on SBFs, especially in rural regions, and calls for urgent interventions to promote clean cooking and reduce the negative impacts of SBFs.

Production of household cooking fuels

The trend in the production of primary cooking fuels in Ghana is shown in Fig. 2. The production of SBFs is the most popular, reaching 4200 ktoe in 2021. Wood production is widespread, and about 90 % of wood in Ghanaian homes are sourced from the densely forested regions in the transition and savannah zones, mainly from Ashanti, Bono, Ahafo, Western North, Western, and Eastern regions, and logging and sawmill residues (Mawusi et al., 2023b). Firewood production declined from 2742 ktoe in 2000 to 1438 ktoe in 2020, with a 3 % annual reduction rate, though it rose to 1937 ktoe in 2021. By 2021, firewood constituted 45.3 % of the overall wood supply, down from 70.5 % in 2000 (Fig. 2A) (GEC, 2021, 2022a).

Conversely, charcoal production has increased at a compound annual growth rate of 4.82 %, from 1094 ktoe in 2000 to 2807 ktoe in 2020, before falling to 2225 ktoe in 2021. In 2021, charcoal production represented 52.1 % of the total wood supply, up from 28 % in 2000 (Fig. 2A) (GEC, 2021, 2022a). The success of the charcoal industry can be ascribed to its proper regulation and the involvement of producers, merchants, transporters, wholesalers, retailers, and key mediators such

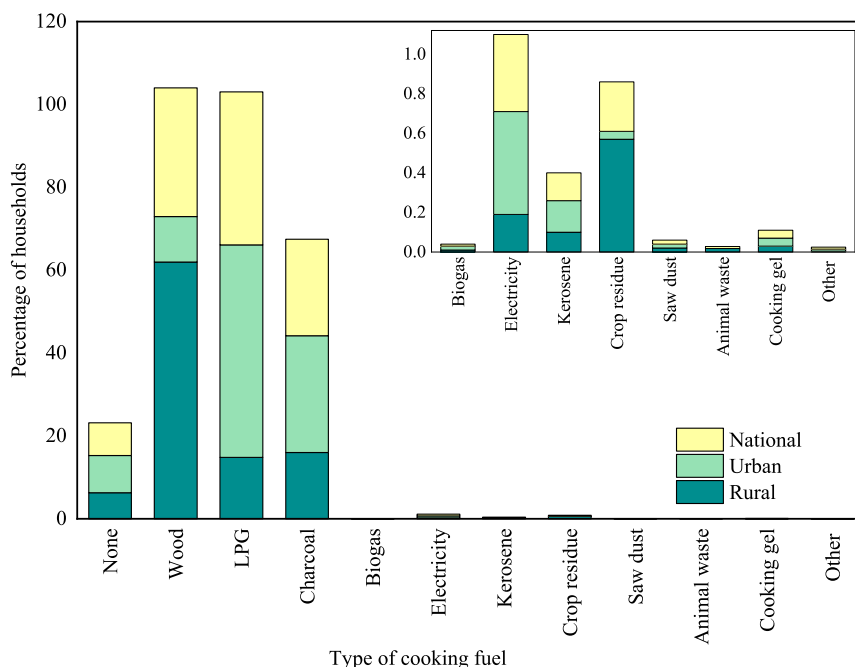


Fig. 1. The percentage distribution of household cooking fuel type in Ghana (GEC, 2022a; GSS, 2021b).

Table 1

Comparison of clean cooking technologies and traditional solid biomass fuels (Champion et al., 2021; Jetter et al., 2012; Mawusi et al., 2023b; Mperejekumana et al., 2024; Shen et al., 2018). PM_{2.5} and CO emission factors are presented as milligrams of individual pollutants per megajoule of useful energy delivered (mg/MJ_d).

Cookstove	Fuel	PM _{2.5} (mg/MJ _d)	CO (mg/MJ _d)	Benefits	Limitation
Traditional	Wood, charcoal	759–1150	15.7–16.1	Low upfront cost, cultural familiarity	Severe HAP, deforestation, health risks
LPG	Propane/butane	2.39–2.63	0.036–2.3	Eliminates indoor air pollution, faster cooking	Fuel cost volatility, supply chain gaps
Electric	Grid/renewable electricity	N/A		No fuel dependency, integrates with renewables	Requires stable electricity access
Improved biomass	Wood	101–161	2.48–4.60	Retains cultural practices, transitional solution	Still reliant on biomass fuels
Biogas	Charcoal	38–162	12.9–22.4		
	Methane (organic waste)	N/A		Converts waste to energy, reduces greenhouse gas emissions	Requires organic waste infrastructure
Solar	Solar thermal energy	N/A		No fuel costs, ideal for off-grid areas	Weather-dependent, slower cooking
Pellet/Briquette	Compressed biomass residues	21.6–40.8	2.21–2.94	Utilizes agricultural waste, efficient combustion	Requires strong supply chain and infrastructure

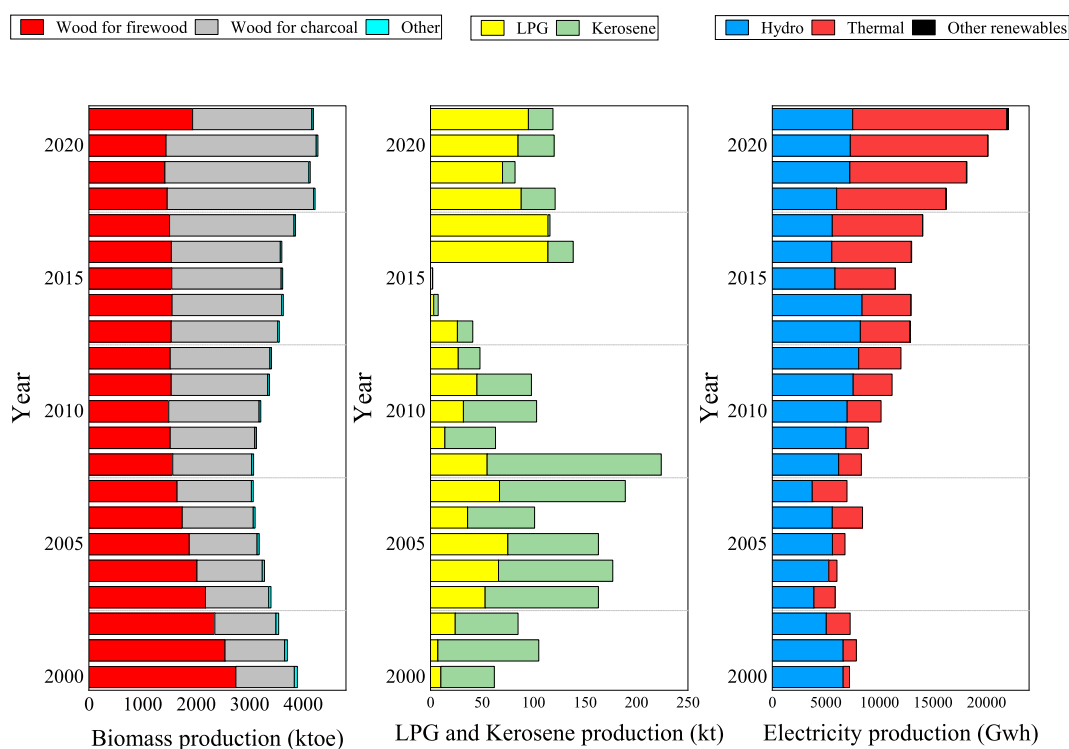


Fig. 2. Trend in main household energy production in Ghana (Afful-Dadzie et al., 2022; GEC, 2021; Kemausuor et al., 2015; Takase et al., 2022).

as the Ghana Forestry Commission, District Assemblies, chiefs, land-owners, and the police (Agyei et al., 2020). Significant charcoal production occurs in the Bono East and Eastern Regions, particularly in Kintampo, Atebubu, Nkoranza, and Afram Plains (Agyei et al., 2018). In 2018, charcoal sales generated about GHS 310 million annually, mainly in cities like Accra, Ksoa, Kumasi, and Takoradi (Agyei et al., 2018; Brobby et al., 2019). Generally, the total biomass supply in Ghana grew at an annual average rate of 0.35 % from 2000 to 2021.

Electricity generation, critical for enabling electric cookstoves, has shifted dramatically in its production mix (Fig. 2C). More details on electricity power stations in Ghana can be found in Section S4. In 2000, hydropower dominated Ghana’s grid (92 % share), primarily from the Akosombo Dam, but its contribution fell to 34.1 % by 2021 due to droughts, siltation, and aging infrastructure (Afful-Dadzie et al., 2022; GEC, 2021, 2022a). Thermal plants - powered by imported natural gas and diesel - now supply 65.3 % of electricity, exposing households to volatile fuel prices and tariffs (GEC, 2022a). Renewables, mainly solar, contribute only 0.55 %, despite Ghana’s high solar potential (4.4–5.6 kWh/m²/day), reflecting underinvestment in decentralized clean

energy solutions (Aboagye et al., 2021; Opoku et al., 2022). Total electricity generation nearly doubled from 11,200 GWh in 2011 to 22,051 GWh in 2021, with hydro contributing 7521 GWh, thermal 14,408 GWh, and renewables 122 GWh (Afful-Dadzie et al., 2022; GEC, 2021, 2022a).

LPG, kerosene, and other petroleum products are locally produced and imported (Asante et al., 2018). LPG production, through the Tema Oil Refinery and Atuabo Gas Processing Plant, increased by 12 % from 10 kt to 95 kt, while kerosene production dropped by 34 % from 52 kt to 24 kt between 2000 and 2021 (Fig. 2B) (GEC, 2022a). This thermal-heavy electricity mix has critical implications for clean cooking adoption. Although 86.1 % of households have access to electricity, frequent outages and high tariffs hinder electric cookstove use (Afful-Dadzie et al., 2022; GEC, 2022a). Rural off-grid communities, reliant on biomass, remain excluded. Though solar and biogas offer scalable off-grid alternatives, they require policy support and are yet to be included in the energy mix (Aboagye et al., 2021). The decline in firewood usage from 2742 ktoe in 2000 to 1438 ktoe in 2020 reflects a gradual shift towards clean cooking fuels like LPG. However, the

increase in charcoal production, which grew at a yearly rate of 4.82 % from 2000 to 2020, indicates a continued reliance on SBFs.

The trends in the production of cooking fuels in Ghana are consistent with findings from other studies in sub-Saharan Africa. For example, studies in Uganda (Nsamba et al., 2021), Rwanda (Nshimiyimana et al., 2024), and Malawi (Mortimer et al., 2017) highlight the challenges of transitioning from traditional SBFs to cleaner alternatives like LPG and electricity. Despite its environmental impacts, the increase in charcoal production in Ghana, reflects broader regional trends where charcoal remains a dominant fuel source due to its affordability and availability. Other studies also highlight that charcoal will remain a popular household cooking fuel in sub-Saharan African countries beyond 2030 (Mwampamba et al., 2013). These findings stress the need for targeted interventions to promote clean cooking and reduce reliance on SBFs. Clean cooking will not be widely available in the short term due to financial and infrastructure constraints (Boudewijns et al., 2022), and thus SBFs will remain widespread in many developing countries, including Ghana. Therefore, past studies suggest that developing the cookstove/fuel system in tandem, producing cleaner SBFs like biomass pellets, and burning green charcoal in improved cookstoves will aid clean cooking and yield significant health and environmental benefits (Wathore et al., 2017).

Cost of major household cooking fuels

Fig. 3 shows the trend in price for LPG, kerosene, and electricity in Ghana. There has been a 2.5 %, 2.7 %, and 2.3 % increase in the price of LPG, kerosene and electricity in Ghana since 2000 (GEC, 2006b, 2019b, 2021, 2022a). Although very popular, the pricing of wood and charcoal for household cooking is carried out on the indigenous scale and is not formalized nor regulated (Partey et al., 2017). The same goes for biomass pellets, as it is still nascent in Ghanaian households (Mawusi et al., 2023b). Thus, the average price per kilogram of wood, charcoal, and biomass pellets in Ghana are GHS 0.43, GHS 1.22, and GHS 3, respectively (GEC, 2022b; Mawusi et al., 2023b). The SBF markets in

developing countries, especially in sub-Saharan Africa, are mostly informal, leading to significant fuel price variations and lack of regulation. This observation is also evident in Uganda, Malawi, Nepal, among others (Guta et al., 2022; Rakos & Prauhart, 2023).

The Ghanaian clean cookstove market

Available cookstoves

Ghana's clean cookstove market features a growing range of technologies designed to reduce emissions and improve efficiency (Fig. 4). Improved biomass cookstoves, such as the Philips gasifier and Envirofit wood stoves, are increasingly adopted for their ability to reduce emissions relative to three-stone fires (Bawakyillenuo et al., 2021b; Morelli et al., 2017). The Gyapa improved charcoal stove, a government-promoted model, dominates the charcoal sector due to its energy efficiency and carbon credit financing (Coffey et al., 2017; Mawusi et al., 2023b). The 4 - burner stove with oven is favored among LPG users. Some households employ electric cooking technologies like rice cookers and microwaves (GSS, 2021b; Sakah et al., 2019). Emerging alternatives like biomass pellet/briquette cookstoves and ethanol cookstoves are becoming popular (Akolgo et al., 2021; Owusu et al., 2019; Pennin et al., 2009). In Ghana, cooking areas vary based on household location, size, and economic status, ranging from indoor to outdoor spaces and shared to separate areas (Shupler et al., 2024). Between 2012 and 2015, over 3200 firewood and pellet cookstoves were distributed through government and institutional efforts (GEC, 2016). Additionally, more than 910,200 improved charcoal, firewood, and bio-gel cookstoves have been disseminated for residential cooking (GEC, 2012, 2016). The Government of Ghana aims to have 1000 commercial users and 3 million households adopt improved, energy-efficient biomass cookstoves by 2030, emphasizing scalability (Afful-Dadzie et al., 2022; GEC, 2019a). Like other regions, stove stacking practices like mixing LPG with traditional biomass fuels, is common among Ghanaian households (Dickinson et al., 2019). This observation highlights the need for

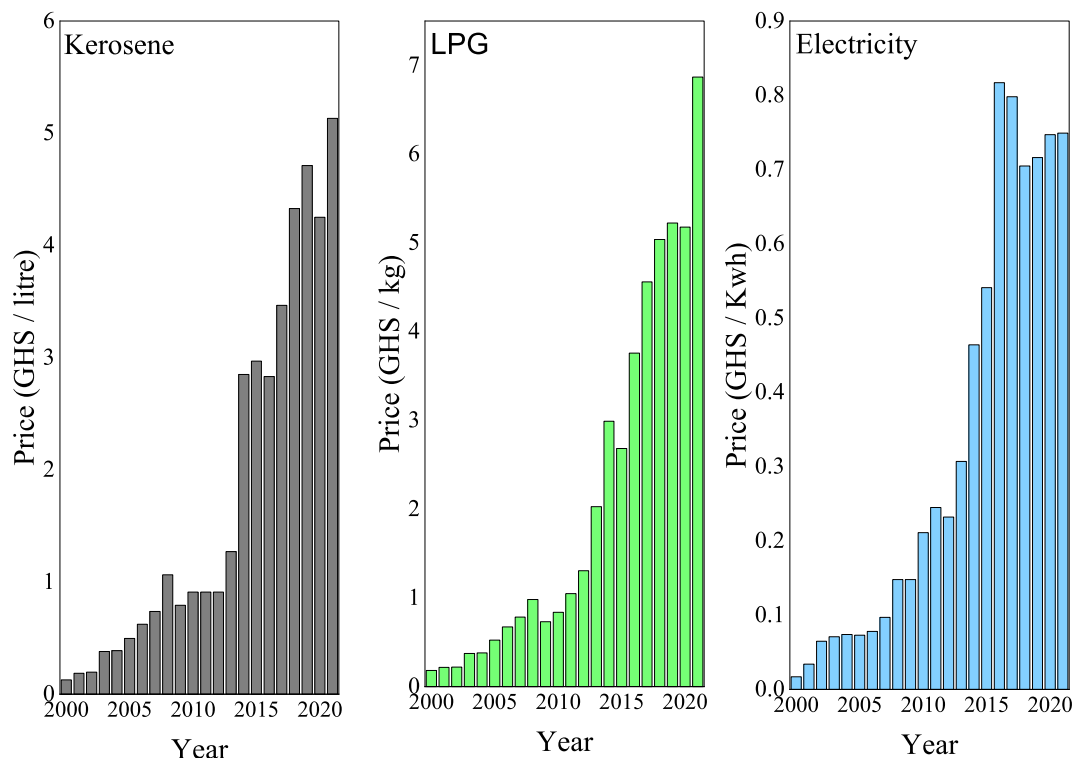


Fig. 3. Price trend for modern household cooking fuels in Ghana between 2000 and 2021 (GEC, 2019b, 2021, 2022a).

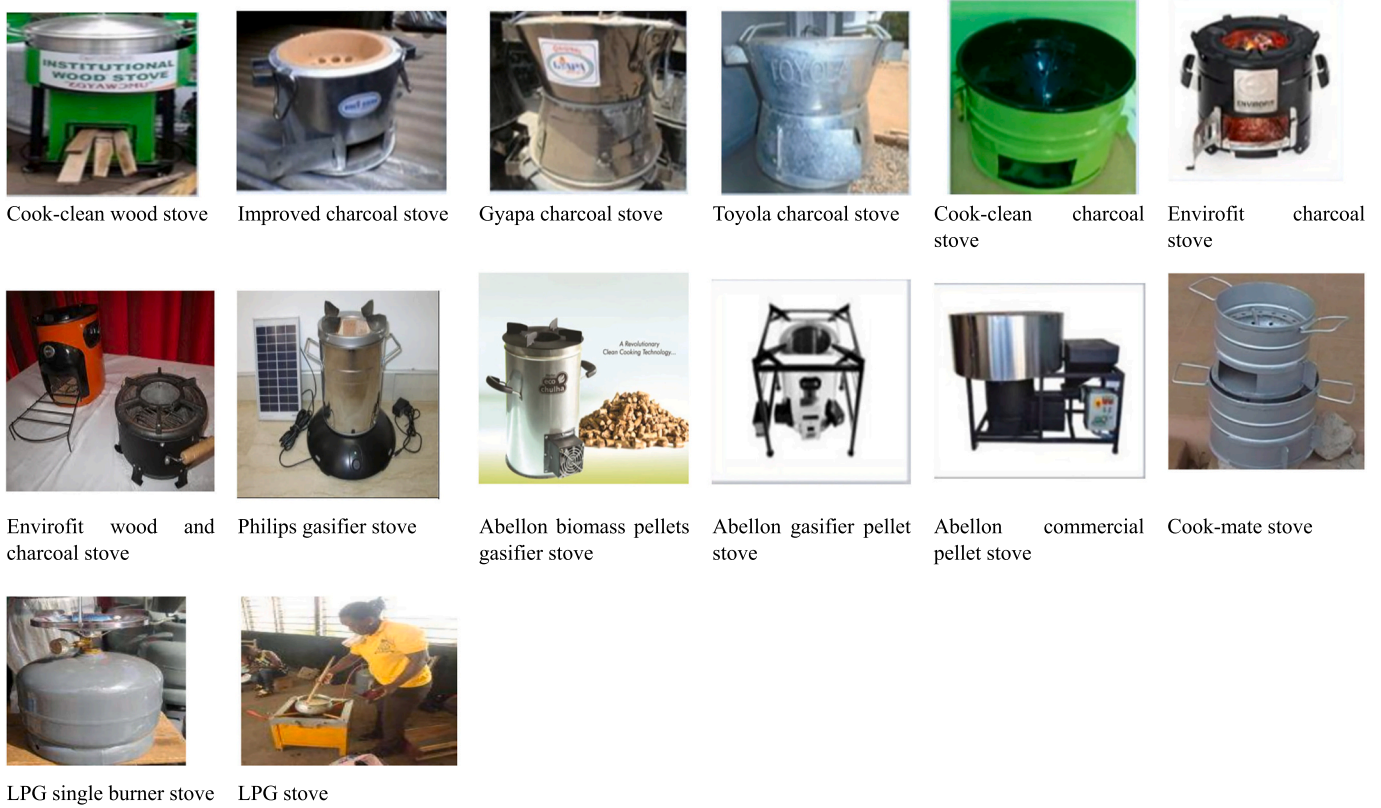


Fig. 4. The types of clean cookstoves used in Ghana (ACEGL, 2020; Bawakyillenuo et al., 2021b; GEC, 2014).

behavioral interventions to ensure sustainable clean cooking transitions.

Cookstove manufacturers

Fig. 5 shows the distribution of cookstove manufacturers in Ghana, totaling 87 manufacturers. Most (97 %) are local or artisanal, while the rest are associated with Abellon Clean Energy Ghana Limited, Gyapa, and Philips Stove Companies (GEC, 2014). The Ashanti, Greater Accra, and Central regions have the highest number of manufacturers, with 25, 15, and 10, respectively. Six regions (Western North, Bono, Bono East, Oti, Savannah, and North East) have no information on stove manufacturing firms, though there might be small-scale local or artisanal ones [43]. Cookstoves in Ghana are made from various materials, including mild steel, tire rims, scrap metal, aluminum, and cast iron, with lifespans ranging from 2 to 5 years (GEC, 2014).

Price of cookstoves

Table 2 shows the prices of popular household cookstoves in Ghana. The average price ranges between GHS 3 and GHS 56 for manufacturers and GHS 6.4 and GHS 56 for retailers (GEC, 2014). The average market price of wood cookstoves is the lowest, while LPG cookstoves are 622 % more expensive than wood cookstoves. In Ghana, the market prices of cookstoves exceed those quoted by stove manufacturers by 97 % - 300 %. The SBF cookstove market has significant penetration compared to the clean cooking market (Section S5).

National policies targeting the promotion and implementation of clean household cooking

Fig. 6 provides a comprehensive overview of key policies and incentives in Ghana that facilitate promoting and implementing clean cooking. More details are shown in Section S6. The pivotal policies

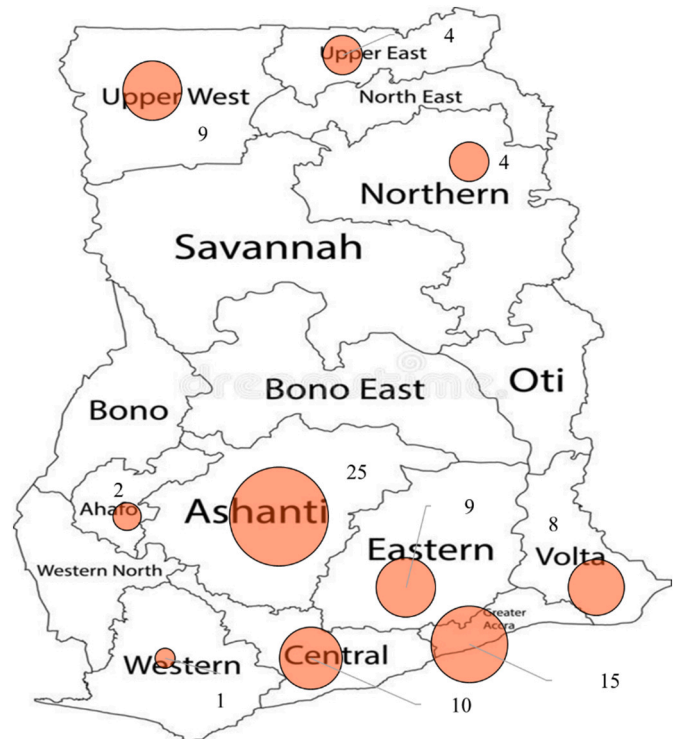


Fig. 5. The number of cookstove manufacturers per region in Ghana (ACEGL, 2020; GEC, 2014). The size of the bullets corresponds with the number of cookstove manufacturers per region.

Table 2
Price of cookstoves in Ghana in 2014 (Bawakyillenuo et al., 2021b; GEC, 2014).

S/ N	Type of cookstove	Manufacturers quote		Market quote	
		Price range (GHS)	Average price (GHS)	Price range (GHS)	Average price (GHS)
1	Traditional Charcoal stove (Scrap metal)	2.5–4.0	3	2.5–25	9
2	Tradition charcoal stove (Mild steel/ aluminum cast)	5–30	14	6–45	15
3	Tire Rim Charcoal stove	20–30	25	12–60	26
4	Improved Charcoal stove	12–36	17	10–36	18
5	Firewood stove (Scrap metal)	5–7	7	5–7	6.4
6	Tire rim Firewood stove	–	–	12–60	22
7	Sawdust stove	–	–	5–7	6.5
8	LPG stove (Local)	35–120	56	20–90	56

driving Ghana’s cookstove sector include the Renewable Energy Act, National Energy Policy, Renewable Energy Master Plan (REMP), Liquified Petroleum Promotion Program, National Energy Strategy, Energy Sector Strategy and Development Plan (ESSDP), Sustainable Energy for All (SE4All), and Ghana Energy Development and Access Project (GEDAP) (Afful-Dadzie et al., 2022; Agyekum, 2020; Awuku et al., 2022; GME, 2010). Over the years, the government has demonstrated a strong commitment to improving household cooking by promoting clean cooking transitions, developing relevant policies, and supporting these initiatives with financial mechanisms such as incentives and assistance from foreign and local donors (Mawusi et al., 2023b). By examining these policies, stakeholders can gain valuable insights into the regulatory framework and incentives driving the country’s transition towards cleaner and more efficient cooking solutions.

Challenges hindering clean cooking technologies

Environmental and health impacts

Many Ghanaian households, especially in rural areas, experience severe levels of HAP due to wood and charcoal burning, resulting in significant health impacts (Nazif-Muñoz et al., 2020). HAP contributes to 502,000 disability-adjusted life years (DALYs) and 18,000 premature deaths annually, representing 2.2 % of Ghana’s national disease burden from solid fuel use (Armah et al., 2015). Forecasts suggest that wood and charcoal demand will rise, comprising 23 % of total energy demand by 2030 (Kemausuor et al., 2015). Practical solutions are needed to address health issues associated with increased reliance on traditional cookstoves and fuels. Additionally, despite using stoves such as the Gyapa stove, improved stoves in Ghana still need to substantially reduce HAP (Coffey et al., 2017; Delapena et al., 2018). Table 1 indicates that clean technologies like LPG, electric cookstoves and improved biomass cookstoves reduce PM_{2.5} emissions linked to respiratory diseases, while the converse is observed for traditional SBFs. Also, the continued reliance on SBFs for household cooking is associated with the 60 % decline in Ghana’s forest cover and other alarming environmental implications (Asamoah et al., 2020). These observations highlight the need for transitioning to clean cooking technologies.

Accessibility and affordability

Access to clean cooking in Ghana remains a significant challenge, impacting its adoption and sustained household use (Nuhu et al., 2022). This issue is particularly evident in the northern regions, where manufacturing and retail stores for clean cookstoves are scarce (Adams et al., 2023) (Section S7). Only 31 % of Ghanaians have access to clean cooking (Adams et al., 2023; GSS, 2021b). Access to LPG and electric cookstoves is limited by longer distances to retail outlets and unreliable electricity supply (Asante et al., 2018). The limited availability and affordability of clean cookstoves buoy the dominance of wood and charcoal stoves and restrict consumer choice and preference (GEC,

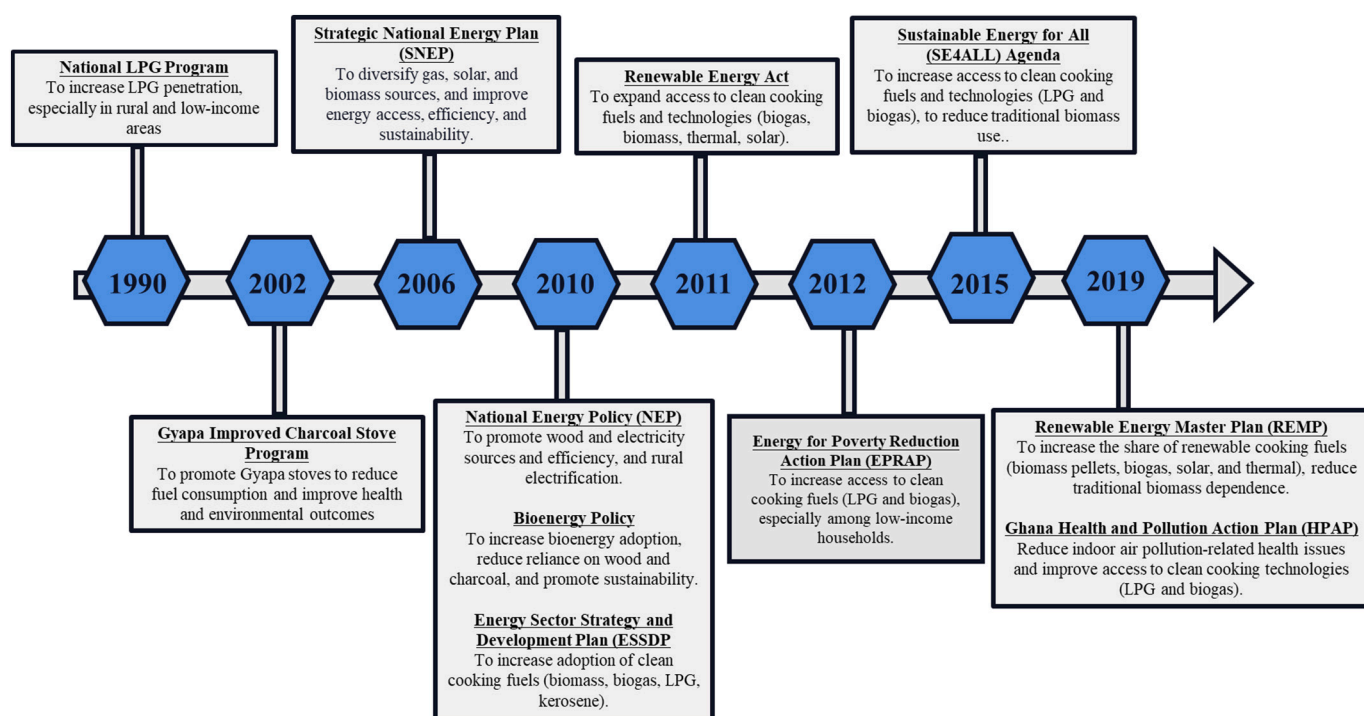


Fig. 6. National policies that target the promotion of clean household cooking energies (Bawakyillenuo et al., 2021a; Gyasi et al., 2022; Iddrisu & Bhattacharyya, 2015; Mawusi et al., 2023b).

2022c). For example, households in the Bono, Bono East, and Ahafo regions were willing to pay GHS 2296 instead of GHS 2870 for a ton of biomass pellets, despite it resulting in a 10 % loss in marginal profit for businesses (Akolgo et al., 2021). Furthermore, household energy decisions are influenced by distribution network reliability and local, regional, and national market policies and trends (Guta et al., 2022). In Ghana, the cookstove and fuel market is informal and unregulated, thus leaving pricing and cost dynamics to the vagaries of vendor choices (Partey et al., 2017). Compared with their clean counterparts, the regional production and distribution of networks of wood and charcoal, are well coordinated in Ghana, especially in the northern regions of Ghana, hence their popularity among households (Dongzagla & Adams, 2022). Although Ghana has made significant progress in household electricity access (64 % in 2010 vs 84 % in 2021), inconsistent electricity supply hampers the use of electric cooking technologies nationally and in urban areas (GEC, 2022a) (Section S8). Ghana produces and imports LPG, with local production through the Tema Oil Refinery and Atuabo Gas Processing Plant. In 2021, imported LPG (252 kt) far exceeded local production (95 kt), imposing high financial costs on households (GEC, 2022a) (Section S7). The Unified Petroleum Price Fund scheme by the government aims to incentivize LPG transporters to serve rural areas beyond a 200 km radius of main distribution points. Yet rural LPG penetration remains inadequate (Asante et al., 2018). Also, rural households face long commutes to procure LPG, thus deterring household cooking with LPG (Dalaba et al., 2018). Maintenance services are crucial for adopting cookstove technologies, but repairs and replacements for improved cookstoves are often unavailable, hindering scalability (Abdulai et al., 2018).

In addition, other investigations report substantial financial investment of household cooking in Ghana (Bawakyillenuo et al., 2021a; Dalaba et al., 2018). For example, on average, Ghanaian households spend 3.1 % and 2.7 % of their annual income on LPG and biomass pellets, respectively, compared to 0.7 % and 1.2 % for wood and charcoal (Mawusi et al., 2023b), with significant burden on rural households. About 43 % of the average monthly Ghanaian household income is allocated to food expenses (Bawakyillenuo et al., 2021b). Given the substantial cost of cooking energy, household income greatly influences cooking fuel choices. Urban households in Ghana tend to be more sensitive to price fluctuations in cooking energy compared to their rural counterparts. Thus, the lack of affordable, clean cooking fuels and stoves would financially strain rural residents who adopt them (Adu-Poku et al., 2022; Adusah-Poku & Takeuchi, 2019). Therefore, practical initiatives are essential to facilitate the sustainability of clean cooking transitions in Ghana.

Financial constraints

The primary issue facing clean cooking transitions in Ghana is insufficient funding for research and development (R&D) and dissemination programs (Kemausuor et al., 2015; Sakah et al., 2017). Apart from the Gyapa charcoal stove project, no other stove project is carbon-financed, hence the popularity of Gyapa charcoal stoves in Ghanaian households (Mawusi et al., 2023b). This limits the monetary support for market development initiatives to increase clean cooking access in local communities. Furthermore, only 9 % of the USD 480 billion clean energy budget is allocated to R&D, with the government expecting 80 % of the investment to come from the private sector (Afful-Dadzie et al., 2022; Asante et al., 2022). The government of Ghana would require approximately GHS 310 million, GHS 294 million, and GHS 480 million to achieve 50 % nationwide penetration of improved wood, charcoal, and LPG stoves, respectively, with costs tripling to reach 100 % penetration (Nuhu et al., 2022). However, private investors are hesitant due to uncertainty about returns and productivity on such projects (Agyekum et al., 2021). Therefore, clean cooking projects in Ghana necessitate substantial financial support.

The current progress of the REMP implementation suggests that its

goals may not be achieved without more private investment, as over 90 % of the achieved progress is from private investors (Afful-Dadzie et al., 2022). The high cost of capital is another significant bottleneck to developing clean cookstoves, fuels, and their promotion since most energy projects in Ghana rely on debt financing, leading to high interest rates that hinder business growth (Agyekum et al., 2021). High labor and equipment costs impact the production and promotion of clean cooking technologies, as seen in Argentina, China, and the United States (Jiang et al., 2020; Meng et al., 2021; Shankar et al., 2020). Ghana's reputation for high lending interest rates further hampers clean household energy projects, increasing borrowing costs for companies and limiting their operations (Agyekum et al., 2021). Additionally, exchange rate volatility, particularly with the US dollar, remains a significant concern for Ghanaian cookstove businesses and industries (Agyekum et al., 2021). Cookstove companies, particularly early-stage enterprises, are impacted by timely access to finance, which influences the demand and supply of clean cooking (Adams et al., 2023).

Awareness and education

Social perspectives play a pivotal role in accepting clean cookstoves and fuels in Ghana (Mawusi et al., 2023b). This observation is compounded by a discrepancy between local community perspectives and the country's vision for promoting clean household energy (Ahmed, 2020). There is insufficient public involvement and training in clean household energy programs, especially for inaccessible regions (Francis et al., 2022). A report on the Greater Accra and Upper West regions of Ghana indicated that although all the households had prior knowledge of improved cookstoves, 63 % did not receive any training on using them. The few that did were given oral presentations during sales and promotion programs or through the media and community meetings (Adams et al., 2023). Another significant obstacle to the adoption and use of clean cookstoves and fuels in Ghanaian households is the perception of clean cooking technologies being costly compared with wood or charcoal (Carrión et al., 2020). Household characteristics, income levels, and employment status influence the adoption of clean fuels (Owusu et al., 2015). Due to the large household sizes, type of cooking methods (i.e., smoking, frying, and boiling), and specific taste preferences, most Ghanaian households remain conservative and prefer cooking with open fires and coal pots over their clean counterparts (Guta et al., 2022; Nuhu et al., 2022). Stove stacking - using multiple cookstoves simultaneously, such as combining traditional stoves with clean technologies - poses a challenge, as many households continue to rely on their old stoves alongside new ones, limiting the full adoption of cleaner alternatives. For example, a study among riparian communities of the Volta Lake of Ghana stack improved local mud cookstoves with three stone fires (Mawusi et al., 2024). Other studies in the Northern region of Ghana also report simultaneous use of solid fuel cookstoves for household cooking (Coffey et al., 2017). Cultural preferences for traditional stoves, as seen in Northern Ghana's simultaneous use of improved and three-stone stoves (Dickinson et al., 2019) mirror fuel-stacking behaviors observed in Kenya's Kisumu project. Tailored behavioral interventions, like those trialed in Rwanda (Jagger & Das, 2018; Seguin et al., 2018) could address such challenge.

To date, the Gyapa charcoal stove is the only formalized household cookstove market in Ghana, hence its popularity (Dickinson et al., 2015). Users' conservative preferences regarding food tastes, cooking practices, and fuel accessibility have constrained the uptake of clean fuels (Guta et al., 2022; Nuhu et al., 2022). Despite government efforts, only about 31 % of Ghanaians have access to clean cooking fuels, with many still relying on wood and charcoal (Adams et al., 2023; GSS, 2021b). The national LPG promotion program, targeting 50 % access by 2020, has achieved only 37 % penetration due to logistical bottlenecks (e.g., limited refill stations) and upfront costs (Bawakyillenuo et al., 2021b). While local availability and initial uptake of LPG have improved, low-income households often use it sporadically as a

secondary cooking option or abandon it after a short period (Kar et al., 2024). Apart from the pervasiveness of cookstove stacking, the adherence to cultural tenets and cooking practices hampers clean cooking adoption (Dickinson et al., 2019; Owusu-Amankwah et al., 2023). Also, the REMP-backed biomass pellet projects are yet to commence, due to lack of infrastructure, and the non-inclusion of pellets in Ghana's energy mix (Azasi et al., 2020; Mawusi et al., 2023b). Furthermore, recent reports highlight the importance of peer influence in household fuel choices, particularly in the cultural context of developing countries, emphasizing the need for broader attention to socio-economic and cultural factors in clean energy transitions in Ghana (Wen et al., 2021; Zhu et al., 2022).

Cultural preferences also play a significant role in the adoption of clean cooking technologies in Ghana. Many households, particularly in rural areas, prefer traditional cooking methods using wood and charcoal due to long-standing cultural practices and taste preferences. For example, certain dishes are believed to taste better when cooked over an open fire or in a coal pot. Additionally, the social stigma associated with using unfamiliar technologies, such as LPG or electric stoves, can hinder adoption. To overcome these barriers, it is essential to design clean cooking solutions that align with local cooking practices and cultural norms. Public awareness campaigns and community engagement initiatives can also shift perceptions and encourage the adoption of cleaner cooking technologies. Targeted educational campaigns and hands-on training are urgently needed to shift behaviors.

Supply chain

The adoption of clean cooking technologies in Ghana faces significant challenges due to fragmented and underdeveloped supply chains. Unreliable supply and long distance commutes limits the use of LPG cookstoves in Ghana (Asante et al., 2018). The high import duties and taxes on cleaner cookstoves disproportionately affects low-income households, causes low market penetration and discourages private sector investment in clean cooking technologies, favoring cheaper, informal biomass markets (GEC, 2012). Additionally, local production of advanced clean cooking solutions, such as biomass pellets and gasifier stoves, is limited. Despite Ghana's potential to produce 34.9 million tons of crop residue pellets annually, only a few firms operate at scale, with most production being small-scale and informal, lacking standardization and quality control (Azasi et al., 2020; Mawusi et al., 2023b).

Furthermore, artisanal manufacturers dominate the cookstove market, accounting for 97 % of production (GEC, 2014). While they provide affordable options, their reliance on scrap metal and manual processes results in inconsistent quality, short lifespans and limited scalability of cookstoves. Regional disparities exacerbate the issue, as supply chains are concentrated in urban centers like Ashanti and Greater Accra, leaving northern regions without formal manufacturing units and forcing rural households to rely on costly shipments from cities (ACEGL, 2020; GEC, 2014). Furthermore, the robust informal charcoal supply chain, which dominates rural and urban markets, undermines efforts to promote cleaner alternatives, as charcoal is readily available while other clean cooking technologies are scarce (Agyei et al., 2020).

Infrastructure and technological challenges

Ghana's clean cooking infrastructure lags behind demand. In Ghana, only 25 % of households use improved biomass cookstoves, which mainly burn charcoal and wood (Dickinson et al., 2015; Van Vliet et al., 2019) and biogas/solar technologies are rare due to technical limitations (GEC, 2022a; GSS, 2021b). Intermittent electricity undermines electric stove adoption, despite 85 % grid access (Bloomer & Boateng, 2024). Despite the potential for sawdust briquettes to replace wood and charcoal, their large-scale production ceased abruptly in 1984 due to operational issues and plant breakdowns in manufacturing plants (Akowuah et al., 2012). Additionally, identifying sources and types of

suitable raw materials for producing improved cookstoves or upgrading the existing models is a challenge (GEC, 2019a; Owusu et al., 2019). The discontinuation of Ghana's sawdust briquette production in the 1980s mirrors challenges faced in China's early biomass initiatives, where inconsistent policy enforcement stalled progress (Mawusi et al., 2025). Similarly, Ghana's reliance on informal SBF markets exacerbates deforestation, echoing Malawi's struggles with unregulated charcoal production (Mortimer et al., 2017). Although the Renewable Energy Master Plan (REMP) includes the provision of 3 million biomass pellet stoves to households, there is no primary gasifier stove production firm in Ghana, nor has large-scale production of pellets commenced (GEC, 2019a). Further challenges identified encompass inadequate stove lining, utilization of substandard materials in production, insufficient ventilation due to poor design, restricted availability of maintenance services in various areas, challenges in heat regulation, emission of smoke, and the heating of handles during use, posing safety risks for children (Adams et al., 2023).

Policy issues

Despite growing political support for clean household energy, government commitment to promoting such initiatives remains challenging (Kuamoah, 2020). Moreover, inadequate policy frameworks hinder the transition to clean energy (Obeng-Darko, 2019). In Ghana, the Renewable Energy Master Plan (REMP) aims to increase clean cooking solutions, such as electric cookstoves. However, progress has been slow due to unreliable electricity supply (Afful-Dadzie et al., 2022). Poor coordination among stakeholders in renewable energy planning further weakens commitment to the REMP, leaving Ghanaians largely unaffected by clean cooking energy policies (Francis et al., 2022). Furthermore, many stakeholders remain unaware of the REMP and its implementation strategies, contributing to the modest achievement of only 3.5 % of the plan's target since 2019 (Afful-Dadzie et al., 2022; Appiah et al., 2022). Parts of Ghana's Strategic National Energy Plan (SNEP) have yet to be implemented due to legislative and monitoring issues (Sakah et al., 2017). In Ghana, biofuel projects also need more policy execution and regulatory frameworks (Pueyo, 2018) since their progress is often hampered by delays in execution and lack of supervision. Similarly, the rural LPG Program needs a comprehensive implementation strategy for distributing LPG (Asante et al., 2018). While the National Petroleum Agency is working on a new LPG policy for Ghana that will include an implementation plan for the rural LPG program, progress is hampered by the absence of a structured monitoring and evaluation system (Abdulai et al., 2018). Without proper feedback mechanisms, the effectiveness of the rural LPG remains questionable. The Ministry of Energy continues to uphold the initial goals of the RLP, although its operations and distribution methods have changed over time (GEC, 2006a). Initially, LPG cylinders and cookstoves were distributed at community gatherings, but now, the district assemblies handle the distributions, causing bias in the selection of recipients and other mismanagement practices (Asante et al., 2018; Broni-Bediako & Amarin, 2018). The lack of a clear scaling plan and viable business models stifles the growth of clean cooking. Finally, heavy reliance on donors, insufficient institutional resources, and poor coordination, continue to pose significant challenges to Ghana's clean cookstove sector (Atuguba & Tuokuu, 2020).

Knowledge and data gaps

The challenge with research and data limits the thorough assessment of clean cooking in Ghana. Till now, access to data on households and stove distribution, as well as national statistics on the cookstove sector, is challenging (Mawusi et al., 2023b). Research on HAP and the development of clean cooking technologies in Ghana is also limited. Furthermore, only a few studies have probed into HAP from SBFs (Abdo et al., 2021; Carrión et al., 2019; Daouda et al., 2022; Shupler et al.,

2024). Similarly, few studies have explored designing gasifier cookstoves and their emission-reduction abilities (Antwi-Boasiako & Glalah, 2021; Bofo-Mensah et al., 2021; Bonsu et al., 2020; Commeh et al., 2019; Mawusi et al., 2023a; Mitchual et al., 2014; Osei et al., 2020; Owusu et al., 2019). To date, studies that evaluate the emissions reduction potential of LPG, electricity, biogas, bio-gel, and thermal cookstoves in Ghana are limited. The available studies in Ghana report on common air pollutants such as CO and PM_{2.5}, although volatile organic compounds, polycyclic aromatic hydrocarbons, nitrous oxides, ultrafine particles, and the chemical composition of PM_{2.5} are vital to policymaking about the effectiveness of clean cooking transitions and public health (Bilsback et al., 2019). Closing these gaps requires increased funding for interdisciplinary research and robust national energy databases.

Opportunities and suggestions for promoting clean cooking in Ghana

There is a growing potential for adopting clean cooking in Ghana (Pennise et al., 2009). While LPG and electric stoves have gained some traction in urban areas, rural communities rely heavily on biomass-based cooking methods (Abdulai et al., 2018; Asante et al., 2018). In this section, we explore the opportunities for stove projects and businesses in Ghana, particularly emphasizing on the need for affordable and accessible cleaner cookstoves such as LPG, electric, gasifiers, and solar cookstoves. By analyzing market dynamics, technological innovation, policy support, and capacity-building initiatives, we identify pathways for promoting the adoption of cleaner cooking technologies and advancing sustainable development goals in Ghana. Through collaborative efforts and strategic interventions, stakeholders can unlock the potential of the cookstove sector to improve the well-being of Ghanaian households and contribute to a cleaner, healthier, and more sustainable future. Thus, several suggestions can help improve the cookstove use scenario in Ghana.

Technological advancements

China's deployment of 119 million improved stoves, driven by gasification and solar integration (Zhou et al., 2021) (Zhou et al., 2021), offers a blueprint for Ghana to leverage its abundant solar and biomass resources for scalable clean cooking solutions. While clean cooking technologies such as pellet stoves, electric stoves, biogas cookers, and solar cookstoves have made progress in Ghana, significant technological advancements are necessary to enhance their efficiency, affordability, and usability, particularly in rural and off-grid areas (Adams et al., 2023). Pellet cookstoves, which utilize wood or crop residue pellets, require innovations to improve combustion efficiency and reduce emissions. Automatic feeding mechanisms, adjustable heat control, the inclusion of a tertiary air supply, proper insulation to prevent heat loss in the combustion chamber, and designs that incorporate waste heat recovery can enhance their user-friendliness and energy efficiency (Himanshu et al., 2022; Osei et al., 2020). Also, developing a gasifier stove that can efficiently burn pellets from different feedstock is necessary. Ghana already generates 3 million tons of wood waste and 39 million tons of crop residues annually, and these feedstocks can yield 2.7 and 34.9 million tons of wood and crop residue pellets, respectively, for household cooking (Azasi et al., 2020). Wood and crop residue pellets can replace the current household demand for wood, charcoal, and LPG by 2–5, 3–27, and 5–49 times, respectively, and 19–163, 36–353, and 64–629 times, respectively across all the 16 regions of Ghana (Mawusi et al., 2023b). More details can be found in Section S9. Thus, the development of an efficient gasifier stove will be beneficial to household cooking in Ghana.

For induction and electric stoves, which are tied to electricity availability, advancements in low-power consumption models and the development of hybrid stoves that operate on both grid and off-grid

power would make these devices more practical for areas with intermittent electricity (Opoku et al., 2022; Pablo Ochoa Aviles et al., 2020). Additionally, integrating battery storage or solar-charged systems into electric stoves can mitigate power outages, making them more reliable in remote regions (Odoi-Yorke, 2024; Opoku et al., 2022). Biogas cookers, a clean alternative with significant potential, need further refinement in burner efficiency, material durability, and flame control to maximize the utility of biogas (Jameel et al., 2024). Modular biogas systems that are easier to install and maintain, especially for rural households, would increase adoption rates (Jameel et al., 2024). Currently, Ghana produces 2716 Mm³ CH₄ per year (Table S5). Furthermore, the biogas from waste can replace the yearly total national average biogas cooking demand per household by 3% - 272% (Section S12). Again, the total biogas generated can replace yearly household biogas cooking energy demand in all the regions by 16 times (Section S13) with the highest potential for the Ahafo, Western North, Upper West, Savannah, and North West regions of Ghana (Section S14). However, the design of biogas cooking technologies should be compatible with local cooking habits. Also, ensuring that biogas digesters are well-designed to contain emissions and that waste management practices are environmentally sound is crucial.

Despite Ghana's abundant solar resources, solar cookstoves face practical barriers (Opoku et al., 2022). Ghana has an abundant solar resource of 35EJ, with a monthly average solar radiation of 4.4–5.6kWh/m²/day (Aboagye et al., 2021), which can support household cooking (Section S10). The barriers to solar cookstoves could be addressed by improving heat retention, storage systems, and cooking speed (Aramesh et al., 2019). Solar cookstoves could become a more versatile solution by developing stoves that can store energy for use during cloudy days or nighttime and ensuring the designs are lightweight and portable (Aramesh et al., 2019). Across all clean cooking technologies, emphasis on affordability, user convenience, and durability will be critical to ensuring widespread use. Innovations such as automatic ignition, flame control, real-time fuel monitoring, and using locally sourced materials for production can help reduce costs while enhancing user experience. These technological advancements are crucial for promoting the adoption of clean cooking devices in Ghana, contributing to public health and environmental sustainability and reducing the reliance on traditional biomass fuels. For example, through significant advancements in biomass gasification, anaerobic digestion, direct combustion and other technologies (solar, biogas and electric), China has produced and distributed over 119 million improved cooking and heating stoves to households, which has translated into significant environmental benefits (Du et al., 2018; Zhou et al., 2021).

Establishing stove manufacturing factories

Improving local manufacturing and production facilities for affordable cookstoves can create employment opportunities, stimulate economic growth, and ensure a sustainable supply of clean cooking solutions. Currently, cookstove production in Ghana is predominantly done at an artisanal level, limiting both output and quality (GEC, 2014). By leveraging local resources and expertise, improved cookstoves that are tailored to the needs and preferences of Ghanaian households can be developed (Mawusi et al., 2023a). This approach not only supports the domestic market but will serve neighboring country markets where similar needs and preferences exist. Moreover, investing in training and capacity building for local stove artisans can enhance their skills, knowledge, and capabilities in designing, manufacturing, and maintaining improved cookstoves (Adams et al., 2023; Mawusi et al., 2023b). For example, the establishment of factories by Mimi-Moto and BURN manufacturing in Kenya, Malawi, and Rwanda has buoyed the adoption of gasifiers and other improved cookstoves due to the training and use of local labor (Champion & Grieshop, 2019; Jagger & Das, 2018). When local communities are empowered to produce their cookstoves, it creates sustainable livelihoods, promotes entrepreneurship, and fosters

innovation. By scaling production and expanding market reach, Ghana has the potential to meet both domestic and regional demand, contributing to broader efforts towards clean cooking in West Africa.

Improved sales and distribution of cookstoves

Establishing a comprehensive distribution network that involves local retailers, community-based organizations (CBOs), and micro-finance institutions (MFIs) can significantly enhance the promotion of clean cooking in Ghana (Pode, 2013). Local partners embedded in communities help build trust and offer valuable consumer insights, which are essential for tailoring clean cookstove solutions to meet specific needs (Leary et al., 2021). One example is Inyenyeri, a social enterprise in Gisenyi, Rwanda, that distributes the Mimi Moto pellet-fed semi-gasifier cookstove (Champion & Grieshop, 2019). Their business model focuses on customer service and affordability by offering stoves, fuel delivery, training, and repairs at no extra charge. Customers sign a monthly contract to buy pellets, which are priced competitively with charcoal (Jagger et al., 2019). Apart from that, thorough market research is critical to understanding consumer preferences and constraints, enabling the selection of high-quality, durable, and affordable cookstoves suited to local cooking habits (Ackah et al., 2021; Mawusi et al., 2023a). Developing efficient distribution routes that reach both urban and rural areas ensures that cookstoves are accessible to all (Boateng et al., 2023). Targeted sales and marketing strategies, and incentives like trade-ins, discounts, and installment plans through MFIs, combined with educational campaigns that highlight the health and cost-saving benefits, can increase adoption (Boateng et al., 2023; Del Rio et al., 2020). While Ghana's LPG adoption is rising, lessons from Kenya's Kisumu LPG project where pay-as-you-go models reduced upfront costs and increased adoption by 34 % (Perros et al., 2021; Perros et al., 2023) suggest that flexible financing could accelerate uptake in rural Ghana, where income disparities limit access. Additionally, robust after-sales support, including maintenance services and access to spare parts, is crucial for ensuring sustained use and customer satisfaction (Mawusi et al., 2023b). MFIs play a vital role by offering financing options reducing the financial burden on low-income households. By integrating these elements, a well-structured distribution network can overcome barriers to clean cooking adoption and ensure its long-term success in Ghana.

Rentals or leasing of cookstove models

Introducing rental or leasing models for cookstoves can be transformative in expanding clean cooking solutions across Ghana, especially for rural communities (Gani et al., 2023). These models are designed to alleviate the financial burden of acquiring clean cookstoves, as the high upfront costs are a major barrier for many households (Seguin et al., 2018). By offering flexible payment options, such as pay-as-you-go schemes or installment-based leasing, more households can adopt clean cooking technologies without straining their finances. For example, the use of the pay-as-you-go scheme in a pilot study displaced the use of charcoal and accelerated LPG in 63 (out of 90) homes in urban Rwanda (Perros et al., 2021). Other models, such as lease-to-own, microfinance leasing and subscription, have helped advance hydrogen-based and LPG cooking solutions in rural Kenya (Gani et al., 2023; Schöne et al., 2023). Rwanda's Inyenyeri project, which reduced household fuel costs by 46 % through cookstove leasing and biomass pellet subscriptions (Champion & Grieshop, 2019; Seguin et al., 2018) illustrates how Ghana could adopt similar models to overcome upfront cost barriers, particularly for LPG and electric stoves.

Additionally, these models can integrate essential services such as regular maintenance, repairs, and even upgrades. This integration ensures that households have access to reliable and efficient cookstoves, fostering long-term use and preventing the fallback to traditional cooking methods (Perros et al., 2021). By providing upgrade options,

users can transition to newer, more efficient, or environmentally friendly models as they become available, supporting technological innovation and sustainability. A well-established network of rental outlets, ideally located in both urban and rural areas, will increase the availability of these services. This network will also create local employment opportunities, as technicians and support staff will be needed for training, troubleshooting, and maintenance tasks. These jobs can further stimulate local economies while ensuring that users receive the help they need to effectively use and maintain their cookstoves.

From an engineering perspective, rental and leasing models for cookstoves offer a promising pathway for optimizing zero-carbon grids in built environments. These models can reduce the upfront costs associated with clean cooking technologies, making them more accessible to low-income households. Additionally, the integration of renewable energy sources, such as solar and biogas, into these models can enhance their sustainability and reduce reliance on fossil fuels. For example, Odoi-Yorke (2024) demonstrates the potential of zero-carbon grids in promoting electric cooking in urban and rural settings. By leveraging these engineering innovations, Ghana can develop scalable and sustainable clean cooking solutions that align with global efforts to combat climate change and promote sustainable development. To maximize the success of these programs, continuous monitoring and evaluation of their social, economic, and environmental impacts will be crucial (Gani et al., 2023). By analyzing data on cookstove adoption rates, fuel savings, reductions in HAP, and user satisfaction, stakeholders can adjust their strategies to improve access and efficacy. Additionally, this information will be valuable for influencing policy decisions and scaling up initiatives, ensuring that clean cooking becomes a national priority in Ghana (Adams et al., 2023).

Carbon credit programs

Carbon credit programs can significantly reduce costs associated with cleaner cookstoves by leveraging the financial value of carbon emissions reductions (Francis et al., 2022). As demonstrated by the Gyapa stove project, carbon credits allow manufacturers and distributors to subsidize the production and sale of stoves, passing these savings on to consumers. For instance, by earning revenue from carbon credits, the Gyapa stove initiative can offer its products at a highly affordable price of GHS 25 despite using locally sourced materials that already help reduce costs (Ackah et al., 2021; Bawakyillenuo et al., 2021b). In addition, charcoal stove manufacturers use attractive incentives and advertisements to buoy the sale of their products (Ackah et al., 2021). By scaling up these programs and expanding to other technologies, such as biomass pellets and gasifier stoves, carbon finance can act as a continuous revenue stream (Mawusi et al., 2023b). This financial support would reduce upfront production costs, lowering the price of the cookstoves for consumers (Furmankiewicz et al., 2021). The broader adoption of these cookstoves, driven by affordability, could also attract further investment into clean cooking technologies, creating a positive feedback loop that sustains lower costs over time. These programs should be tailored towards facilitating the promotion of biomass pellets and gasifier stoves in the short to medium term since Ghana has significant amounts of biomass for production, and demand (Azasi et al., 2020). However, about 3 % of the annual average Ghanaian household income (GHS 51,535.41) may be spent on cooking with biomass pellets (Mawusi, Shrestha, Xue and Liu, 2023b), and this will be disproportionately borne by households in the Upper West, Upper East, Northern, Brong Ahafo, Volta and Western regions of Ghana, and even more by their rural areas (Mawusi et al., 2023b). Further efforts are needed to reduce the cost associated with biomass pellets and gasifiers. Other reports also echo that wood and charcoal are expected to remain the dominant fuels in Ghanaian households in the foreseeable future, given their abundance (Aabeyir & Agyare, 2020). Therefore, there is a need for further research and projects to enhance wood-and-charcoal-based cooking technologies, as the synchronized improvements to both

cookstoves and sustainable biomass fuels could offer practical solutions (Wathore et al., 2017). Moreover, these initiatives could reduce household fuel consumption and operational costs by focusing on sustainable biomass fuels and improving stove technologies. Improved fuel use efficiency reduces the need for charcoal or wood, translating to ongoing savings for families (Wathore et al., 2017). For example, BURN manufacturing company in Kenya has so far been supported with over USD 12 million in carbon finance to enable the production and distribution of ~5 million electric, solar and improved solid fuel cookstoves to Ghana, Tanzania, Uganda, among others, saving ~ USD 973 million in household cooking fuel cost (Bapfakurera et al., 2024). With carbon credit programs absorbing some of the financial burden, production and operating costs decrease, making these technologies more accessible to a more significant portion of the population (Furmankiewicz et al., 2021). In essence, carbon credit financing not only incentivizes the production and sale of clean cookstoves but also enhances affordability through economies of scale and reduced fuel usage. This creates a pathway where cost reduction becomes a key driver of widespread adoption, leading to health, environmental, and economic benefits for the community.

Key findings and contribution

This study enhances the discussion on clean cooking in Ghana with important insights and contributions. First, it identifies socio-cultural dynamics, such as entrenched preferences for traditional cooking practices and widespread cookstove stacking, as pivotal barriers to adoption, highlighting the need for culturally aligned behavioral interventions. Also, economic constraints are shown to disproportionately burden low-income households due to unregulated fuel markets and high upfront costs, necessitating innovative financing models like carbon credit programs or cookstove leasing schemes. Furthermore, technological gaps persist, with limited local capacity to produce advanced cookstoves (e.g., gasifiers, electric stoves), while renewable energy integration (e.g., solar, biogas) emerges as a viable solution for off-grid communities. In addition, policy implementation challenges, including fragmented stakeholder coordination and inadequate monitoring frameworks, weaken initiatives like the Renewable Energy Master Plan, highlighting systemic governance issues. Finally, the environmental and health impact of biomass use, linking it to 60 % forest cover loss and approximately 18,000 annual premature deaths (Adu-Poku et al., 2022; Asamoah et al., 2020; Nuhu et al., 2022), stresses the urgency for scalable interventions. By bridging the socioeconomic, cultural, and technical gap analysis in previous studies, this work provides actionable pathways for policymakers to accelerate Ghana's transition to clean cooking while addressing SDGs 7 and 13.

Future prospects and research directions

The transition to clean cooking in Ghana requires forward-looking policies and targeted research to address persistent gaps and emerging challenges. Future policy initiatives should prioritize scaling carbon credit programs to subsidize clean cooking technologies, as demonstrated by the success of the Gyapa stove project. Strengthening Ghana's Renewable Energy Master Plan (REMP) to include decentralized renewable energy systems (e.g., solar, biogas) for off-grid communities could accelerate adoption. Additionally, enhancing rural LPG distribution through public-private partnerships and revising tax regimes to incentivize local manufacturing of advanced cookstoves (e.g., biomass pellet gasifiers cookstoves) would address affordability and accessibility barriers. Policymakers must also establish robust monitoring frameworks to evaluate the implementation of existing programs like the National LPG Promotion Program, ensuring equitable reach across socio-economic and geographic divides.

Future research should adopt interdisciplinary approaches to understand the socio-cultural dynamics influencing stove stacking and

long-term adoption. Longitudinal studies on behavioral changes after cookstove interventions could inform tailored awareness campaigns. Techno-economic analyses and lifecycle assessments of emissions from clean fuels are critical to validate their environmental benefits. Comparative studies with successful models in Rwanda (Inyenyeri pellet stoves) and Kenya (pay-as-you-go LPG) could identify transferable strategies for Ghana. Finally, exploring the role of digital platforms in streamlining supply chains and financing mechanisms presents an available opportunity for innovation. Addressing these priorities will bridge existing knowledge gaps and foster evidence-based policy-making, aligning Ghana's clean cooking transition with global sustainability agendas.

Conclusion

This study provides a comprehensive analysis of the clean cooking landscape in Ghana, highlighting the persistent reliance on traditional biomass fuels despite the availability of cleaner alternatives. The findings emphasize the multifaceted challenges - ranging from affordability and accessibility to socio-cultural and infrastructural barriers - that hinder the widespread adoption of clean cooking. However, the study also identifies significant opportunities for improvement, including technological advancements, local manufacturing, enhanced distribution networks, innovative financing models like carbon credit programs, and rental or leasing schemes. The success of initiatives such as the Gyapa Improved Cookstove project demonstrates the potential for scalable, sustainable solutions that align with local needs and preferences.

To achieve meaningful progress, a holistic approach is essential. Successful models like Gyapa (Ghana), Inyenyeri (Rwanda), and China's biomass policies emphasize that affordability, cultural alignment, and carbon financing are critical for transitioning from solid biomass fuel dependence. Ghana's path forward hinges on adapting these lessons to local contexts through targeted policy, financing, and community engagement. Policymakers must prioritize context-specific interventions that address the unique socio-economic and cultural dynamics of Ghanaian households. Strengthening regulatory frameworks, increasing financial support for research and development, and fostering public-private partnerships will be crucial. Additionally, integrating renewable energy sources like solar and biogas into the cooking energy mix can provide sustainable solutions for rural and off-grid communities.

By addressing these challenges and leveraging emerging opportunities, Ghana can make significant progress towards achieving the United Nations Sustainable Development Goals (SDGs) for clean and affordable energy (SDG 7) and climate action (SDG 13). Future studies should prioritize comparative analyses of cookstove sustainability, including lifecycle emissions and long-term environmental trade-offs, to inform context-specific technology adoption. This study offers actionable insights and strategies for stakeholders, emphasizing the need for collaborative efforts to drive the transition to clean cooking, ultimately improving public health, environmental sustainability, and economic well-being across the nation.

CRedit authorship contribution statement

Sylvester Mawusi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Prabin Shrestha:** Writing – original draft, Visualization, Validation, Methodology. **Daniel Nukpezah:** Writing – review & editing, Supervision, Resources, Formal analysis, Conceptualization. **Francis Kemausuor:** Writing – review & editing, Visualization, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly and DeepSeek in order to review the language and writing style. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esd.2025.101727>.

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