Adoption and impacts of clean bioenergy cookstoves in Kenya

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ABSTRACT

Kenya is one of the leading countries in the development and commercialization of clean bioenergy stoves in Sub-Saharan Africa. However, due to a series of interconnected factors, the adoption and sustained use of clean bioenergy stoves remains low in the country. This study synthesizes the current knowledge about clean and efficient bioenergy stoves in Kenya through a comprehensive review that brings together the disparate knowledge about the context, status, adoption and impacts of clean bioenergy stoves in Kenya. We start by outlining the main national policies technological, options and stakeholders involved in the clean bioenergy stove value chain such as government agencies, private companies, research organisations, and the civil society. Despite their different roles and interests, there is a shared expectation among all involved stakeholders that clean bioenergy stoves will curb the negative sustainability impacts of traditional cooking options on energy security/ poverty, human health, rural livelihoods, gender equality, and the environment. However, a series of factors affect the adoption and sustained use of clean bioenergy stoves such as market structure, consumer awareness, stove design/performance, and the socioeconomic status and cultural practices of stove users. We develop a conceptual framework that illustrates the interlinkages between these factors of adoption and impacts, and outline their varying degree of importance in Kenya. We finish this review by suggesting six policy and practice domains that need to be targeted by policies and research if an effective transition towards universal clean cooking is to be achieved in Kenya. These include to (a) adopt integrated policy approaches and enhance stakeholder collaboration; (b) raise awareness of the benefits of clean bioenergy cooking options; (c) facilitate access to funding and establish appropriate economic incentives; (d) implement quality assurance mechanisms; (e) facilitate behavioural change amongst stove users; (f) enhance research, development, and technical capacity.

1. Introduction

Access to modern, clean and reliable energy affects practically every aspect of economic development and human wellbeing [1]. Energy demand, supply and use is tightly interlinked with multiple environmental and socioeconomic issues, and has emerged as one of the major sustainability challenges in Sub-Saharan Africa (SSA) [13,14]. Access to modern and sustainable energy has moved at the forefront of international policy discourse and has been enshrined in a dedicated Sustainable Development Goal (SDG7) that aims at “ensuring universal access to affordable, reliable, sustainable and modern energy for all by the year 2030”. Progress for SDG7 will partly be measured through the promotion, adoption and sustained use of clean fuels and energy technologies [15].

Currently, approximately 780 million people in SSA (out of 915 million) use traditional biomass such as fuelwood, charcoal and animal dung in open fire and inefficient stoves for their daily cooking and heating [1,2]. Such cooking practices have been linked to poverty, energy insecurity, gender inequality, and unhealthy living conditions [3–7]. For example, several studies have reported the dangers of using traditional inefficient cookstoves [5,8–10], and especially the health complications arising from exposure to indoor air pollutants [6], which cause an estimated 600,000 premature deaths annually [11]. At the same time, traditional and inefficient cooking practices can potentially have severe environmental impacts, especially linked to ecosystem degradation and greenhouse gas (GHG) emissions [12].

Clean cooking technologies that can substitute traditional and inefficient biomass stoves/fuels have become key elements in efforts aiming to curb the negative sustainability impacts of energy access and use in SSA [16,17]. Clean cooking encompasses “cooking facilities which are used without harm to the health of those in the household and which are more environmentally sustainable and energy efficient than biomass
**Cookstoves and the Three-Stone Fires** [1]. This includes various technological options such as improved solid biomass stoves, biogas systems, liquefied petroleum gas (LPG) stoves, electric cookers, ethanol stoves, and solar stoves, all of which either do not use solid biomass or use it more efficiently compared to traditional stoves such as a “three-stone fire” [18–20].

Clean cooking has gained high visibility into policy and practice, and has been a cornerstone of numerous international initiatives. The Global Alliance of Clean Cookstoves (GACC) has been at the forefront of international efforts related to the adoption of clean and efficient cookstoves and fuels by 100 million households by 2020 [19,21]. Since GACC’s launch in 2010, approximately 82 million stoves and fuels (including 53 million clean and efficient cookstoves) were disseminated globally through GACC partners between 2010 and 2015 [22]. Another relevant international initiative is the Sustainable Energy for All (SE4All), a global platform that aims to facilitate access to modern energy for all by 2030. SE4All has identified clean cooking as one of its high impact opportunities [23]. The World Bank launched in 2010 its Biomass Energy Initiative for Africa (BEIA) that seeks to modernise the biomass energy sector in SSA, and incorporate it into the organization’s lending portfolio. The World Bank also launched in 2012 the Africa Clean Cooking Energy Solutions (ACCES), which aims to develop a market-transformation program that can enable scaling up the adoption of clean cookstoves in SSA through enterprise-driven approaches [22,24,25].

However, despite all these international initiatives, the adoption of clean cooking options has been notably slow throughout SSA [26]. Kenya is a good example of the current situation. Although it has been among the pioneers of clean cookstove development, marketing and distribution in SSA [2], only 6% of Kenyans have access to clean cooking fuels and technologies [1,27]. In fact more than 80% of Kenyan households (7.2 million households) still depend on woody biomass for their household energy needs [28]. Most of these households can be described as “rural” and “resource-poor”, and face disproportionately their household energy needs [28].

In order to curb these negative effects, the clean cooking sector has evolved rapidly in Kenya. Currently there are various stove and fuel options available to consumers, and a strong policy push to promote clean cooking throughout the country. Numerous local and international companies, programmes and projects, produce, import and disseminate different types of clean cookstoves and fuels, either commercially or under carbon market schemes. These also include international development organisations such as the German Development Agency (GIZ) and Practical Action that have supported local artisans to design, assemble and disseminate clean stoves [31,32].

However, even though Kenya is widely regarded as a model African country for improved cookstoves, there is a fragmented knowledge about the impacts of different cooking practices, and the factors that influence the adoption of clean cooking interventions.

The main aim of this literature review is to synthesize the disparate current knowledge about clean and efficient bioenergy cooking in Kenya. We focus on clean bioenergy cooking options such as improved biomass stoves, biogas stoves, biomass gasifier stoves and ethanol stoves, as they have attracted extensive policy attention and form the backbone of clean cooking interventions in Kenya.

In particular, we synthesize the current knowledge about the policies (Sections 2.1–2.2), technologies (Section 2.3), stakeholders (Section 2.4), impacts (Section 3) and factors of adoption (Section 4) of clean bioenergy cooking options in the country. Our extensive literature review draws evidence from about 300 unique peer-reviewed papers, policy documents and technical reports, and develop a conceptual framework to illustrate the interlinkages between these factors and their varying degree of importance for the country (Section 5.1). We then identify six policy and practice domains that need to be targeted by policies and research if an effective transition towards universal clean cooking is to be achieved in Kenya (Section 5.2). In this respect this review is the most complete and comprehensive attempt to bring together the very disparate body of knowledge about the status, adoption and impacts of clean bioenergy stoves in Kenya.

### 2. Status of Clean Bioenergy Stoves in Kenya

#### 2.1. Biomass Supply and Demand

Biomass fuels dominate final energy use in Kenya. Biomass provides approximately 68% of the final energy use nationally [33], and 98% of domestic energy use in rural areas [34]. Various socioeconomic and environmental factors such as income, location, land use and cultural values, norms and practices affect the levels of biomass energy use in Kenya [32,36,37].

Fuelwood and charcoal account for approximately 70% of the biomass energy used for cooking and heating [35]. In 2010, more than 82% of Kenyan households (7.2 million households) relied on biomass for cooking, with fuelwood and charcoal being the main cooking fuel to 68.7% and 13.3% of households respectively [27,38,39]. Only 1.6 million households use predominately use other cooking fuels for cooking, including paraffin (11.5%), liquefied petroleum gas (LPG) (5%), and electricity (1%) [27].

Forests and woodlands cover about 7% of the country and provide about 45% of the biomass energy resources [32,40]. Farmlands provide the remainder woody biomass, as well as other biomass resources such as agricultural residues and animal dung [41–44]. Conventional methods of fuelwood harvesting and charcoal production (e.g. inefficient earth kilns) contribute substantially to deforestation, land degradation, biodiversity loss, and greenhouse gas emissions [45].

However, the charcoal industry contributes approximately KES 32 billion (USD 450million) annually to the Kenyan economy [32]. Charcoal production and trade has been legalized, with the Kenya Forest Service (KFS) handling the relevant regulations and permits. However, there is an overlap of mandates among the government agencies that relate to the charcoal value chain, which complicate the management and regulation of the woodfuel industry [32].

There is a large discrepancy in the national supply and demand, which cause a large annual wood supply deficit. In 2010 this wood supply deficit was estimated at 10.3 Mm³ of wood [34]. Biomass energy supply and demand are expected to increase by 20.0% and 21.6% respectively by 2032, which will cause the fuelwood and charcoal deficit reach 18.3% and 19.1% respectively [46] (Fig. 1).

The low levels of biomass supply have been linked to several factors such as (a) inadequate management practices, (b) lack of alternative fuels, (c) forest conversion to agriculture and human settlements [39,47–49]. On the other hand, the high biomass demand has been linked to the (a) growing population, (b) higher dependence on wood, (c) inefficient processing and utilization technologies across the entire value chain [39,47–49]. The combined effect of the above has contributed to the degradation of fuelwood stocks and has forced agrarian communities utilize animal dung and crop residues for cooking (rather than for fertilisers) [34,50,51]. Eventually all of the above have accelerated illegal charcoal production and forest loss [40,46,52].

It is in this context of a rapidly increasing biomass fuel demand and decreasing supply that efficient cooking options are promoted in Kenya. There is an expectation that the widespread adoption of such cooking options can help address the woodfuel supply deficit, and its associated negative environmental and socioeconomic impacts [32,40,47,53].
Kenya has a long history of policies, plans and programmes in the energy sector (including for biomass energy) [54–56]. Table 1 outlines the main recent energy policies and strategies in Kenya, and their link (or lack thereof) to clean bioenergy cooking options.

The Sessional Paper No 4 of 2004 articulates the overarching energy policy framework to realize economic growth in Kenya (Table 1). One of its key elements is the promotion of cost-effective, affordable and high quality energy services nationally in the period 2004–2023. This policy has framed several aspects of domestic cooking energy, including targets to catalyse the rate of adoption of efficient charcoal stoves in urban areas to 80% (by 2010) and to 100% (by 2020). Respective adoption targets for rural areas were 40% for 2010 and 60% for 2020. This energy policy also aimed to catalyse the adoption of efficient fuelwood stoves to 30% by 2020. Furthermore, there were prescription to (a) provide training to Jua Kali artisans 2 at the village level to improve the manufacturing, installation and maintenance of renewable energy technologies (including efficient cookstoves) and, (b) provide education on the appropriate use of biomass fuels to enhance public health [57].

The Energy Act No 12 of 2006 amended and consolidated several of the disparate energy policies but did not include any specific provisions for the promotion of clean bioenergy cookstoves (Table 1). However, in 2013, a miscellaneous provision related to improved biomass cookstoves was added through the intervention of the Clean Cookstoves Association of Kenya (CCAK). This provision was perceived to be crucial for the development of the Sustainable Energy for All Action Agenda. In particular this provision provided regulations for the (a) licencing of manufacturers, importers, distributors, technicians, and contractors of improved biomass cookstoves, and the institutional use of biomass fuels for cooking and heating; (b) provision of warranties to customers, and (c) disposal of stoves following other prevailing national environmental laws. This provision categorically defined improved biomass cookstoves as those that comply with the Kenya Standard KS 1814-1:2005.

The 2013 National Climate Change Action Plan (NCCAP) established provisions from the mitigate of (and adaptation to) climate change (Table 1). This policy estimated that the introduction of improved cookstoves and alternative cooking fuels could save up to 5.6 million tCO₂e annually. The NCCAP also formulated the Nationally Appropriate Mitigation Actions (NAMAs) that identify clean cooking as one of its Low Emission Development Strategies [58]. This NAMA expects that the promotion of clean cooking manufacturing and the development distribution centres can improve stove trade, licensing, and capacity building, having ripple effects for national poverty reduction.

Finally, the Energy Bill of 2015 consolidates a series of energy laws and regulations (Table 1). It establishes a regulatory framework in the energy sector that aligns the powers and functions of national government agencies, and outlines the responsibilities of it devolved structure. Table 2 outlines relevant government entities and their stipulated responsibilities. Unlike its preceding energy policies, the Energy Bill of 2015 does not include any provisions for the promotion of clean bioenergy stoves.

The overarching driver behind most of these energy policies has been the need to modernise the production, processing, distribution and consumption of energy (and particularly) biomass energy [54,59]. This was seen as particularly pressing in respect of the rapid urbanization that has increased the demand for charcoal, and raised concerns over resource degradation and energy insecurity [32,47,61–63]. Other underlying drivers include the need to accelerate economic growth, income equality and poverty alleviation [46,54,64–66]. To achieve these policy requirements the aforementioned policies include numerous measures and interventions that seek to facilitate energy transitions, expand sustainable biomass supply, capitalise on recent technological innovation, and promote overall enabling conditions [52,60].

However, the implementation of the existing energy policies and legal framework is hindered by the demand-supply imbalance of biomass energy (see Section 2.1) [67]. Policy implementation is also hindered by the insufficient investments in the biomass energy sector due to prevailing perceptions that biomass energy is inferior to other energy options such as electricity [68].

It is worth mentioning that until recently the national government was solely responsible for policy formulation and implementation. Other key stakeholders in the bioenergy and stove value chains (see also Section 2.4) have had limited participation in the development of energy policies, plans and programmes that sought to promote clean bioenergy cooking options [10,32,35,54,68–70]. However, recent experiences suggest that Kenyan policymakers are either unaware of (or ignorant about) the importance of traditional biomass fuels (and the absolute necessity to tackle issues related to their demand, supply and use) [54,71,72]. More importantly cooking energy seems to have been a marginalised (or even neglected) topic during the formulation of energy policies and related interventions in Kenya [55]. This is despite evidence that suggests that the adoption of an integrated set of measures that can formalise and modernise the biomass energy sector, could catalyse the successful implementation of current energy policies [73].

In fact, it has been suggested that improved, clean and energy-efficient bioenergy stoves (referred to as clean bioenergy stoves for the remainder of the review) can contribute in several aspects of these policies. For example, clean bioenergy stoves can increase fuel efficiency by 25–60% and reduce significantly indoor air pollution compared to the traditional three-stone fire [81,84,86]. Kenya is a pioneer country for the promotion of different types of clean bioenergy stoves such as improved biomass stoves (Section 2.3.1), biomass gasifier stoves (Section 2.3.2), biogas stoves (Section 2.3.3), and ethanol stoves (Section 2.3.4).

2These are clusters of informal metalworking artisans that operate near marketplaces. These artisans sell directly to end-users or work with last-mile distributors.

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Table 1
Main energy policies in Kenya and provisions to promote clean cookstoves.

<table>
<thead>
<tr>
<th>Policy/Legislation</th>
<th>Overall aim</th>
<th>Provisions</th>
<th>Actions to promote clean cookstoves</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomass energy</strong></td>
<td>✓</td>
<td>✓</td>
<td>✓ - Mainstreams gender issues in energy planning</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Initiates programmes for promotion of (and education for) improved stoves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Increases the efficiency levels and rate of adoption of charcoal and fuelwood stoves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Requires the training of local stove artisans</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Puts provisions for the promotion of renewable energy technologies (incl. biomass)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Does not mention explicitly energy efficient cookstoves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Promotes energy efficient cookstoves as a means of catalysing lifestyle and livelihoods interventions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Includes provisions for subsidies and tax waivers for poor households to acquire energy efficient stoves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Supports the use of improved biomass cookstoves and LPG cookstoves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Requires the increase of awareness of improved cooking practices and stove quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Requires pilot initiatives to promote the use of LPG fuel and stoves</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Includes provisions to increase access to soft loans, build the capacity of stove producers, and improve access to testing facilities</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Establishes requirements for improved biomass stove alongside the entire stove value chain in terms of licensing, standardization, warranties and disposal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Acknowledges that kerosene stoves cause indoor air pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— Incentivizes consumers to switch to clean household energy options</td>
</tr>
<tr>
<td><strong>Cookstoves</strong></td>
<td>✓</td>
<td>✓</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>— N/A</td>
</tr>
</tbody>
</table>

Sessional Paper No. 4 of 2004 on Energy, [74]
Lays the policy framework for sustainable, cost-effective, affordable and adequate quality energy services.

Energy Act No. 12 of 2006, [75]
Amends and consolidates the law relating to energy. Provides clauses for the establishment, mandate and functions of the regulatory authority.

The Kenya Vision 2030, [76]
Outlines the national long-term development blueprint for Kenya.

Kenya National Climate Change Response Strategy (2010), [77]
Establishes measures for addressing the challenges posed by climate variability and change.

The National Climate Change Action Plan, (NCCAP) 2013, [78]
Identifies the key priorities to successfully achieve a low-carbon, and climate-resilient growth in Kenya to realize the ambitions of Vision 2030.

The Energy (Improved Biomass Cookstoves) Regulations, 2013 (Miscellaneous provision to Energy Act No. 12 of 2006), [79]
Provides regulations for the manufacturers, importers, distributors, technicians and contractors of improved biomass cookstoves.

National Energy and Petroleum Policy, 2015, [80]
Ensures the affordable, competitive, sustainable and reliable supply of energy to meet development needs at the national and county scales, while protecting the environment.

The Energy Bill of 2015, [81–85]
Consolidates energy laws to establish the functions and mandates of national and local government in relation to energy.
convenient to use. [102] have been tested in laboratories for thermal efficiency, and reportedly con- 

of the imported mobile models has been very high, especially in the 

extensive field tests and continuous modification [91]. However, the 

stoves [91]. This allowed the evolution of the stove design through 

the incorporation of design elements and features found in traditional 

urban and 16% of rural households. Its use has spread to neighbouring 

raising through demonstrations and marketing campaigns [92]. The 

implementation of this initial program was due to the (a) training of 

local artisans that use locally available materials, and focus 

2.3.3. Biogas stoves

The design and development of biomass gasifier stoves follows the Anderson and Reed model of biomass combustion gasifier units [107]. In principle, the biomass fuel in the form of wood, briquette, coffee husks or animal dung is converted into combustible gas through controlled pyrolysis, yielding clean heat and charcoal as a by-product [48,105,108,109]. Different variants include the natural draught design and the forced air design, with their main difference relating to how the airflow is fed to the combustion chamber.

Gasifier stoves have been highly promoted in Kenya through the Kenya Industrial Research and Development Institute (KIRDI) that has developed prototypes for testing following the Anderson and Reed design. The char by-product can be used as a soil amendment to increase farm yields [103]. The gasifier system has reportedly reduced poverty among smallholders and improved indoor air quality in some rural areas of Kenya [107]. However, the high initial cost (approximately USD 35), difficulty during operation, low stove stability and the risk of burns from the hot galvanized wall are major challenges for its wide promotion [110].

2.3.3. Biogas stoves

Biogas is produced through the anaerobic fermentation of biomass, animal slurry and other organic waste [112] (Fig. 2). It contains approximately 50–70% CH$_4$ and 30–50% CO$_2$ depending on the substrate input [113]. Biogas is increasingly becoming popular among small-scale dairy farmers in rural communities as a means of producing both clean and reliable fuel, and organic fertilizer from the bio-slurry [114,115].

Historically, Kenya was among the first African countries to embrace biogas technologies in the early 1950s. By 1986 there were about 200 installed biogas plants, but fewer than 25% were actually operational [111]. The uptake remained low for several years until the Kenya National Domestic Biogas Programme (KENDBIP) was rolled out in 2009, under the Africa Biogas Partnership Programme (ABPP) [115,116]. Within its first phase (2009–2013), the programme constructed 11,529 biodigesters and provided investment subsidies to
<table>
<thead>
<tr>
<th>Year of inception</th>
<th>Stove name</th>
<th>Technological description</th>
<th>Stove images (Cr: [83–85])</th>
</tr>
</thead>
</table>
| 1900s             | Traditional *jiko* stove    | – Introduced by Indian railroad laborers  
– Charcoal stove made of scrap metal and assembled by local tinsmiths (cottage industry scale)  
– Uninsulated. Radiates heat radially and to the pot  
–Retail at KES 35–45 per unit  
– Lasts about one year at full use. However the metal grate needs replacement after three months at a cost of KES 10 | ![Stove Image](image1.png) |
| 1981              | *Umeme (power)* Stove       | – Promoted by UNICEF  
– All-metal, double-walled, charcoal stove with an insulating layer between the two walls. Weighs about 6.5 kg  
– Features an outer body with a door frame and a sliding door to control the air intake in the inner cylindrical combustion chamber  
– High fuel efficiency due to the enclosed combustion chamber. Good convective heat transfer to the inserted pot, insulated chamber walls and regulated airflow  
– Remains hot for a long time, cooks fast and is durable. The large firebox diameter provides stability.  
– Retail at KES 97–125 at a production cost of KES 60 per unit  
– The stove body last 3–4 years at full use. The metal grate needs replacement after 6–12 months at a cost of KES 15–20 | ![Stove Image](image2.png) |
| 1982              | *Kenya Ceramic Jiko (KCJ)*  | – Funded by USAID and implemented by the Ministry of Energy  
– Charcoal stove made predominately of ceramic and some metal elements  
– The ceramic lining reduces heat loss from lateral radiation and increase stove durability  
– The design features an inlet for draught control and perforated grate for ash collection, three hinged triangular-shaped flaps to hold one cooking pot, stove legs for support and a handle.  
– Retail at KES 125–250 at a production cost of KES 100 per unit | ![Stove Image](image3.png) |
| 2006              | *Jiko Kisasa*               | – Promoted by GIZ (EnDev-Kenya)  
– Fixed stove with a combustion liner made from clay designed to use fuelwood, crop waste and other biomass fuel.  
– Fuel is fed through a single opening at the front of the stove.  
– No chimney, but can reportedly produce less smoke than an open fire  
– Uses 40% less fuelwood compared to the traditional three-stone stove  
– The price for the ceramic liner varies between KES. 250–12,000 depending on the size. An extra KES. 50–250 is required as installation fee if it has to be fixed in the kitchen | ![Stove Image](image4.png) |
| 2006              | *Fixed-brick rocket stove*  | – Promoted by GIZ (EnDev-Kenya)  
– Wood stove made entirely from ceramics using rocket stove principles (i.e. burning small pieces of wood in a high temperature combustion chamber)  
– The design of the pot rest allow for the easy transfer of the generated heat to the cooking pot  
– Thermal efficiency of 24–32% and 30% smoke reduction compared to the three-stone stove  
– The price for the rocket stove varies between Ksh. 1200–10,000 depending on the type of material used and the size of the stove | ![Stove Image](image5.png) |
reduce upfront costs (each biogas plant received a flat subsidy of KES 25,000). Phase 2 (2014–2017) aimed to install a further 27,500 biogas digesters, but without financial assistance through subsidies [117].

In parallel to the KENDIP, various private and carbon-finance investments have promoting different biogas designs such as the floating dome, fixed-dome type, tubular/balloon digesters [113,118,119]. The Nairobi River Basin Biogas Project is among the most successful CDM projects in Kenya. This programme aims to construct about 10,000 domestic biogas digesters (of 2–3 m³ capacity) in rural households in Kiambu country that own a minimum of two zero-grazing cows [120].

Despite this boom in the development of biogas units, about 30% of the installed units may not be operational due to poor design/construction, low end-user awareness of best management practices, and poor water supply [121]. The Kenya Standard 2520:2013 established parameters to ensure that Kenyan biogas stoves and digesters are efficient, safe and durable [122].

### 2.4. Ethanol stoves

Ethanol stoves have been promoted less compared to the improved bioenergy stove options discussed above. The United Nations Development Programme (UNDP) launched in 2011 a pilot ethanol stove/fuel project with local micro-distilleries in Kisumu County. The particular stove design has an efficiency of 65%, reduces indoor air pollutant emissions and has flame characteristics similar to an LPG stove [123]. This pilot project intended to establish the necessary structures for the commercialization of ethanol fuel and stoves in Kisumu Country. It aimed to define the market, identify user preferences, and determine possible environmental and socioeconomic benefits [28,51,124].

Consumers Choice Ltd has recently developed a denatured ethanol gel used in specialized stoves. In particular, the ethanol stove uses non-pressurised denatured fuel canisters (1.2L) that contain the ethanol fuel. The stove burner flame is controlled or extinguished through a regulating lever. The high viscosity of the ethanol gel minimizes the risk of accidental spillage. The ethanol fuel is produced in Kenyan sugar factories and is then shipped to Tanzania for processing into a viscous yellow liquid. The final fuel is then shipped back to Kenya for packaging and distribution through Moto Poa Ltd. [3]

### 2.4. Clean bioenergy stove value chain

The clean bioenergy stove value chain in Kenya consists of different stages, namely (a) raw material extraction, (b) stove production and assembly, (c) stove distribution and retail, (d) stove end-use [125] (Fig. 3). Due to the diversity of stove technologies and designs (Section 2.3), various stakeholders are involved in the Kenyan clean bioenergy stove value chain (Table 4).

Apart from those stakeholders that are directly involved in the production and delivery of clean bioenergy stoves, there are various other stakeholders that have vested interest in clean bioenergy cookstoves (Table 4) [122]. These include government agencies, NGOs, research organisations, donors and international organisations. Even though these peripheral stakeholders are rarely involved in the actual delivery of cookstoves, they play an extremely important for the successful integration of clean bioenergy stoves.

### 3. Impacts of clean bioenergy cookstoves

#### 3.1. Energy security and energy poverty

In 2000, fuelwood accounted for 89% of the household energy use in rural areas (741 kg/person/year) and 7% in urban areas (691 kg/person/year) [126–128]. However, biomass stocks in Kenya are declining (Section 2.1). There are substantial concerns about how the looming fuelwood scarcity will affect the (primarily poor) households that rely on fuelwood and charcoal for cooking [129–131].

Clean bioenergy stoves tend to have higher fuel efficiency, compared to traditional biomass stoves, requiring less fuel to achieve the same cooking outcomes. Thermal energy efficiency improvement has

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*Fig. 2. Household biogas stove in operation (photo taken by author).*

*Table 3 (continued)*

<table>
<thead>
<tr>
<th>Year of inception</th>
<th>Stove name</th>
<th>Technological description</th>
<th>Stove images (Cr: [83–85])</th>
</tr>
</thead>
</table>
| 2013 (Kenya)      | Jikokoa³  | - Commercialized by Burn Manufacturing Ltd  
- Mobile charcoal stove, designed in the USA and manufactured in Kenya.  
- Has a fuel efficiency of 48% and can reportedly achieve 60% smoke reduction  
- Incorporates a high-efficiency combustion chamber, light-weight ceramic insulation and insulated handles and has an ashtray designed to collect ashes and for draught control  
- Retails at KES. 4000–5000 depending on location | ![Stove Image] |

³ Germann and Westhoff [86]. Stove Images: A Documentation of Improved and Traditional Stoves in Africa, Asia and Latin America.

³ Photo credit: GIZ EnDev – Kenya.

³ Photo credit: Photo by author.

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been identified as a key measure to reduce excessive fuelwood use for cooking, and at the same time deliver improved energy services [132–135]. Various water-boiling tests (in lab settings) and kitchen performance tests (in real settings) have quantified the efficiency improvement and fuel savings of improved bioenergy stoves in Kenya. Such tests have reported high fuelwood savings (25–60% depending on stove characteristics) compared to traditional three-stone stoves [129,136,137]. Similar studies have also shown that cleaner cooking options can have substantial time-savings by reducing the time invested in fuelwood collection and cooking (on average 4–6 h per day per family) [138–140].

Depending on the technology and design (Section 2.3), the adoption of clean bioenergy stoves can reduce (e.g. improved biomass stoves) or eliminate altogether (e.g. biogas stoves) fuelwood use (Table 5). This can improve the energy security of the (predominately poor) households that depend on traditional biomass stoves [124,141], and reduce household vulnerabilities to fuel scarcity, e.g. due to escalating fuel prices [142] or increasing time requirements for fuelwood collection (e.g. travelling longer distances) [124,129,143].

The monetary savings from the procurement of cooking fuel [141,144–146] can be diverted to meet other basic household needs. This can be especially beneficial for low-income households that reportedly spend about 15% of their income on cooking fuel [14]. However, the cost of procuring and maintaining an improved bioenergy stove needs to be taken into consideration, as such costs might be substantial for poor households [147,148]. The saved time can be invested to pursue other livelihood and educational activities (Sections 3.4–3.5), especially for women and girls (Section 3.7).

3.2. Ecosystems and climate

By reducing the amount of charcoal/fuelwood use or switching to a totally different fuel (Section 4.1), clean bioenergy stoves can reduce impacts on ecosystems and the climate (Table 5). For example, traditional biomass stoves require extensive amounts of fuelwood and charcoal that is often sourced or produced from natural forests and woodlands (Section 2.1). Unsustainable fuelwood harvesting often degrades such ecosystems [17], causing deforestation and land degradation in Africa [42,149] and Kenya in particular [150,151]. This in turn reduces species habitat, and contributes to the loss of biodiversity [152] and multiple ecosystem processes and services such as watershed functions [43,153,154], carbon storage [32,41,62,137,155,156] and soil fertility/health [17]. Several studies have pointed to the ecosystem benefits that a switch toward cleaner bioenergy cooking alternatives can have [157–161].

Biomass combustion in inefficient stoves can also emit large amounts of greenhouse gases (GHG). These emissions affect the global climate [149,150] and have been estimated at 1.0–1.2 Gt CO₂ yr⁻¹ (or 1.9–2.3% of global GHG emissions) [58,162–165]. On the contrary, clean bioenergy cooking options generally emit less GHG due to their different fuel and/or higher efficiency [153,163,166–168] (Section 2.3). Switching to clean bioenergy cooking options can have substantial GHG emission savings estimated at 1–3 TCO₂ yr⁻¹ per stove [152,154–157]. Finally, some clean bioenergy cooking options, such as biogas, can further reduce direct and indirect GHG emissions by capturing and using methane (CH₄), a potent GHG, and substituting chemical fertilizers [165,170,171].

3.3. Health and safety

The inefficient fuel combustion in traditional biomass stoves emits large amounts of indoor air pollutants such as fine particulate matter (e.g. PM₂.₅), carbon monoxide (CO) and nitrogen oxides (NOₓ) [5,172,173]. Women, girls and young children spend are particularly exposed to such pollutants as they spend substantial amounts of time in kitchens (that are also often poorly ventilated) [107,174–176].

It was estimated that about 4.3 million premature deaths globally (600,000 in Africa, 14,300 in Kenya) are linked to indoor air pollution, largely from cooking with traditional biomass fuels [177,178]. Some of the most common health complications include respiratory diseases, chronic obstructive pulmonary disease, eye irritation, cataract, headaches and burns [179,180]. Additionally, cooking-related indoor air pollution has been linked to adverse pregnancy outcomes such as stillbirth, child survival, low birth weight [181], and increased risk of pneumonia to children below the age of five [6,182–185].

The adoption and sustained use of clean bioenergy cookstoves can reduce indoor air pollution and its adverse health outcomes [106,140,175,186,189] (Table 5). For example, improved stoves can...
### Table 4
Main stakeholders in the clean bioenergy cookstove value chain in Kenya.

<table>
<thead>
<tr>
<th>Stakeholder group</th>
<th>Stakeholders</th>
<th>Role and activities</th>
</tr>
</thead>
</table>
| Private sector                         | Cookstove manufacturers, e.g. Burn Manufacturing Ltd., Afrisol Ltd., Sustainable Energy Strategies Ltd., Flexi biogas, Envirolift, Cookswell Jikos, Moto Psa Ltd., PayGo Energy Ltd., Equity Bank Ltd. | - Design, manufacture and distribute clean and efficient cookstoves, including improved biomass stoves, biogas stoves, ethanol stoves, and biomass gasifiers, among others  
- Sell LPG in small quantities through a product service platform that uses smart metering and a pay-as-you-go approach  
- Provide financing for the acquisition of clean cookstoves  
- Offers the Ecomoto loan, an initiative that employs flexible processing and repayment modalities  
- Design, manufacture and sell clean and efficient cookstoves directly to end-users or work with last-mile distributors  
- Diverse stakeholder group that includes clusters of informal metalworking artisans that are active near marketplaces  
- Develop networks to assist the production, sales and promotion of stoves as local ceramicists, marketers and installers.  
- Diverse stakeholder group that includes various women groups such as the Keyo Pottery Women's Group in Western Kenya that has manufactured and sold stoves since the 1980s. |
| Carbon market developers                | Carbon market ventures e.g. Impact Carbon, My Climate, Carbon Africa Limited, Climate Care | - Generate a market for carbon offsets through the dissemination of clean cooking technologies  
- Register projects in the UNFCCC Clean Development Mechanisms, Gold Standard and other voluntary markets |
| Government agencies                    | Ministry of Energy, Kenya Bureau of Standards                                 | - Formulate energy policy and regulate the energy sector  
- Provide incentives for the adoption of relevant technologies, e.g. through the KENDBIP Biogas program  
- Design and maintain quality standards for locally manufactured and imported stoves  
- Develop testing methods and protocols for biomass and biogas cookstoves |
| Non-Governmental Organisations (NGOs)  | The Clean Cookstove Association in Kenya (CCAK)                              | - Facilitate business capacity development and advocacy for the formulation of clean cooking policies  
- Raise public awareness and induce behavioural change for clean cooking practices  
- Accelerate the production, deployment, and use of clean and efficient cookstoves and fuels  
- Offer funding, research, and logistical support  
- Undertake economic feasibility assessments for clean cooking interventions  
- Formulate a cohesive and targeted advocacy agenda to strengthen women involvement in clean energy access and entrepreneurship  
- Support innovative projects, initiatives and business models related to clean cooking  
- Provide financial/technical assistance, resources and facilities to innovators to realize their ideas, develop management and business skills, and grow their businesses |
| Academia and research organisations    | The University of Nairobi African Center for Technology Studies, Kenya Industrial Research and Development Institute (KIRDI), Stove Testing Center, Kenya Forest Research Institute (KeFRI), Stockholm Environment Institute (SEI) World Agroforestry Center (ICRAF) | - Provide market intelligence  
- Test the efficacy of the stoves introduced in the national market  
- Undertake Research and Development, and design of energy efficient cooking technologies  
- Champion the expansion of biofuels and other renewable energies pathways  
- Carry out research on woodfuel characterization (e.g. charcoal, fuelwood) and biomass gasification  
- Influence policies related forest resource management  
- Conduct research and implement projects related to environmental and development challenges, including energy access, and sustainable biomass production and use |

(continued on next page)
reduce CO and PM$_{2.5}$ emissions [171,175]. Based on various studies that have quantified pollutant concentrations in kitchens, traditional stoves and clean stoves result in ambient PM$_{2.5}$ concentration of 300 $\mu$g/m$^3$ and 70 $\mu$g/m$^3$ respectively [169,187,188]. However, to achieve the maximum health benefits, there is a need to prioritise the use of clean fuels at the community level to meet the WHO’s air quality guidelines for CO and PM$_{2.5}$ emissions [187,190].

It should be noted that fuelwood collection often requires venturing over long distances and carrying heavy loads on the back or head. Such practices increase the likelihood of injuries and other adverse health effects [106,181,191], harassment and other forms of violence [192]. Due to their lower fuel requirement, clean bioenergy stoves reduce substantially the frequency of trips (and the time spent per trip) for fuelwood collection. Hence they can reduce the drudgery and associated health effects (e.g. back pains) related to fuelwood harvesting [144]. This in turns frees up time for rest, child caring, education or involvement in income-generating activities, especially for women and girls [107,111,112] (see Sections 3.4–3.6).

### 3.4. Income and employment

Multiple employment and income opportunities can be generated across the clean bioenergy stove value chain (Section 2.4), including in stove design, manufacturing, marketing, distribution and sales [101,111–113] (Table 5). This includes some high-skilled jobs that can provide sufficient income for decent living [140]. For example in 2016, GIZ reportedly created about 1000 jobs in stove production in different private enterprises in Kenya [54,96].

Some clean bioenergy cooking options such as biogas can even generate employment and income outside the stove value chain, e.g. for masons, plumbers, and civil engineers that build the biogas infrastructure [193,194]. Similarly the clean bioenergy stove sector can theoretically provide an alternative market for ethanol feedstock smallholders (e.g. cassava, sugarcane), diversifying their market options. However, actual evidence of this pathway is still anecdotal considering the small penetration of ethanol stoves in Africa [20].

However, the promotion of clean bioenergy stoves can have important livelihood trade-offs. In particular the fuelwood and charcoal sector are major sources of rural employment and income in Africa [195,196], and Kenya in particular. Approximately 200–350 jobs/TJ are generated across the charcoal value chain [197], while commercial biomass energy value chains employ about 13 million people across SSA [198]. Fuelwood and charcoal production constitute a large proportion of the informal economy in Kenya. Approximately 635,000 people are involved [195], contributing an estimated US$1.6 billion per year to the national economy [101,104,111,199,200]. However, the increasing reliance on imported stoves can curb local employment and income opportunities both in the stove value chain (e.g. stove production, marketing, and instalment) [6,54,96,197,201] and the fuelwood-charcoal value chain. Such livelihood trade-offs need to be considered when promoting clean bioenergy cooking options.

### 3.5. Education

As discussed above, traditional stoves require higher quantities fuelwood. This in turn requires substantial time investment for fuelwood collection and cooking. These tasks are often assigned to young children, especially girls, whose time could have otherwise been invested attending school or doing homework [195]. Similarly, overburdened parents often prevent children from attending school in order to assist with fuelwood collection and cooking [202]. Clean bioenergy stoves can reduce the time needed for fuelwood collection and cooking, thus offering a real opportunity to improve educational attainment, especially in rural areas [203]. Similarly, clean bioenergy cooking options can free parents’ time, thus enhancing the available time for child care work, e.g. for preparing breakfast for school children [203,204].

Furthermore, clean bioenergy cooking options can offer several benefits to households, such as improved health and reduced drudgery [144]. This in turn allows more time for education and other income-generating activities.
3.6. Food security and nutrition

Relieving school budgets [5,208,209]. Send children to school [207] and improve educational services by school attendance (e.g. school meals can incentivize poor families to receive properly-cooked meals [205,206]). This can both boost financial pressure on school budget and at the same time ensure that availability of clean bioenergy cookstoves in schools can relieving such expense can range between USD 128 and 148 per month [72]. The reportedly spend large amounts to procure fuelwood for cooking school meals. Depending on the number of children and location of the school such expense can range between USD 128 and 148 per month [72]. The availability of clean bioenergy cookstoves in schools can relieving financial pressure on school budget and at the same time ensure that children receive properly-cooked meals [205,206]. This can both boost school attendance (e.g. school meals can incentivize poor families to send children at school) [207] and improve educational services by relieving school budgets [5,208,209].

3.6. Food security and nutrition

The unsustainable fuelwood collection and charcoal production can cause land degradation, desertification and the loss of watershed functions [43,154,210,211] (Section 3.2). These processes place an added pressure on agricultural systems in Africa [49,212] and curb agricultural productivity in some areas [205]. This can possibly reduce food availability and thus cause food insecurity [209].

Furthermore, prevailing fuelwood harvesting and charcoal production can cause the overexploitation of forests, leading to fuelwood scarcity (Section 3.1). Studies have identified the links between fuel-wood scarcity and cooking habits, such as eating half-cooked food, cooking food with low nutritional value that require less cooking time, and not boiling water enough [213]. Other studies have shown that households that use consistently clean bioenergy stoves have higher diet diversity and consume food with higher nutritional quality [175,214,215]. This is because clean bioenergy stoves can allow for the

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Impact mechanisms</th>
<th>Kenya references</th>
<th>Other references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy security and poverty (Section 3.1)</td>
<td>Reduce household vulnerability to fuelwood scarcity through the reduction (e.g. improved biomass stoves) or elimination (e.g. biogas systems, ethanol stoves) of the need for fuelwood and charcoal. Provide economic savings from fuel procurement, which can be invested for other household needs.</td>
<td>[132,134,135,138,140,143]</td>
<td>[126–131,136,137,141,142,144–148]</td>
</tr>
<tr>
<td>Ecosystems and climate (Section 3.2)</td>
<td>Reduce deforestation and habitat loss (and the associated biodiversity loss and ecosystem services degradation) by reducing the demand for fuelwood and charcoal. Reduce the loss of carbon stock and GHG emissions by reducing the demand for fuelwood and charcoal. Biogas systems capture methane reducing overall GHG emissions from livestock rearing and waste management. Biogas systems produce bio-slurry that reduces the demand for chemical fertilizers, which reduces indirectly GHG emissions from agricultural systems.</td>
<td>[112,113,119,137,163,169,170,180]</td>
<td>[163,174]</td>
</tr>
<tr>
<td>Health and safety (Section 3.3)</td>
<td>Reduce the negative health effects related to indoor air pollution (e.g. respiratory diseases, post-pregnancy complication, stillbirths, pneumonia risk) by reducing the emissions of indoor air pollutant through the more efficient combustion of biomass (in improved biomass stoves) or the use of clean fuels (e.g. biogas, ethanol). Reduce the risk of injuries (e.g. burns, scalds) and safety (e.g. house fires) associated with open-fire traditional stoves. Improve kitchen hygiene and home ventilation due to lower smoke emissions. Reduce the negative health effects (e.g. back pains, injuries) of fuelwood collection. Reduce the safety risks (e.g. violence, rape) of fuelwood collection.</td>
<td>[5,107,170,175–177,186,228]</td>
<td>[101,174,190]</td>
</tr>
<tr>
<td>Income and employment (Section 3.4)</td>
<td>Offer opportunities for income generating activities and local employment across the stove value chain. Cause loss of local employment in the charcoal and fuelwood value chains.</td>
<td>[107,112,140,144,227]</td>
<td>[6,197]</td>
</tr>
<tr>
<td>Education and training (Section 3.5)</td>
<td>Boost school attendance by reducing the workload placed on children (and especially girls) for fuelwood collection. Relieve school budgets from high fuel costs, with the monetary savings invested for improving educational activities.</td>
<td>[174,204]</td>
<td>[5]</td>
</tr>
<tr>
<td>Food security and nutrition (Section 3.6)</td>
<td>Prevent the decline of crop productivity due to the loss of ecosystem functions, by reducing pressure on ecosystems (see impacts on ecosystems and climate). Enhance crop productivity by using the bio-slurry generated from household biogas systems as an organic fertilizer. Promote positive diet transitions and improved nutrition through improved cooking and food preparation practices.</td>
<td>[116,207,208,210,211,229]</td>
<td>[80,95,213]</td>
</tr>
<tr>
<td>Women empowerment (Section 3.7)</td>
<td>Reduce burden on women and girls from fuel collection and exposure to indoor air pollution, to allow them rest, pursue an education or engage in income-generating activities. Offer opportunities for engagement in entrepreneurial activities and employment along the clean stove value chain.</td>
<td>[72,180,215,216]</td>
<td>[92,111,207,212,215,220,221,224–226]</td>
</tr>
<tr>
<td>Humanitarian impact (Section 3.8)</td>
<td>Reduce the multiple vulnerabilities that displaced/refugee communities experience. Prevent/reduce conflicts with local host communities over limited biomass resources.</td>
<td>[221]</td>
<td>[201–203,207,222,223,228,230]</td>
</tr>
</tbody>
</table>
easy regulation of the cooking temperature (Section 2.3). This is because clean bioenergy stoves can allow for the easy regulation of the cooking temperature (Section 2.3), allowing the preparation of meals that were previously avoided due to their time-consuming preparation, sensitivity to heat, or high risk of spoilage [181]. Similarly, households can, in theory, invest the saved money and time (see Section 4.1) to improve access to more nutritious food and adopt better food preparation practices [209]. However, currently there is anecdotal evidence of the above mechanisms rather than clear empirical evidence.

Finally, some clean bioenergy cooking options have indirect positive effects to food production. For example, households with biogas systems can use the generated bio-slurry as an organic fertilizer to boost food productivity and crop diversity [216] (Table 5). Furthermore, studies have found higher food crop productivity for households that produce sugarcane for ethanol, due to their better access to fertilisers from their involvement in out-grower schemes [217].

3.7. Women empowerment and gender equality

Most of the leading international organisations involved in the design, promotion, and implementation of clean cookstove interventions such as the GACC, World Bank and WHO have made a strong case that clean cooking can contribute manifold to women empowerment and gender equality [6,19,95,99].

The starting point of their rationale is that most of the negative health and educational outcomes of traditional cooking options are gender-differentiated, in that females face disproportionately the negative impacts (Sections 4.3 and 4.5). In particular, women and girls are usually disproportionately responsible for gathering fuelwood and cooking. For example in Kenya, women reportedly spend at least one hour per day gathering fuelwood for cooking [203], which reduces their available time to pursue activities related to education or paid employment (Table 5). Furthermore, women and girls are much more exposed to indoor air pollution due to cooking [95], and experience higher health and safety risks due to fuelwood collection (e.g. injuries, violence, rape) [218].

Several studies have found that females experience substantially higher negative health outcomes and loss of education/economic opportunities, due to their more substantial time investment in unpaid household work and exposure to indoor air pollution [4,9,21,218–221].

Apart from reducing exposure to indoor air pollutants (Section 3.3) and generating time savings (Section 3.1), clean cookstove value chains create opportunities for women to engage in entrepreneurial activities related to stove design and distribution [219,222] (Section 3.5). The strong engagement of females in such activities can not only enhance gender empowerment [223], but also the adoption and sustained use of clean cookstoves [224] (see Section 5).

3.8. Humanitarian impact

According to 2016 statistics, more than 65 million people have been displaced globally due to conflict, war and natural disasters [225]. Refugees are a particularly vulnerable group, which lives under very difficult conditions and often in conflict with surrounding communities. Most refugee camps in Sub-Sahara Africa have very limited access to reliable energy sources, and almost all do not have clean cookstoves and fuels [208,226]. Even though humanitarian organisations distribute the vast majority of food in refugee camps, they rarely provide, cooking fuel [224]. Thus refugees often depend on traditional wood-based fuel for cooking collected from nearby forests and woodlands.

This lack of reliable and clean cooking energy accentuates all the negative impacts described above (Sections 3.1–3.7). For example, the Moving Energy Initiative has estimated that more than 26,000 ha of forest are lost annually to meet the energy needs of displaced families living in refugee camps [28,51,124]. This enhances the probability of conflict with surrounding communities due to the competition over local (and often scarce) biomass resources [227]. Furthermore, some of the main coping mechanisms for fuel scarcity employed in refugee settings include skipping/undercooking meals, and bartering and selling food for cooking fuel [208]. Negative gender-differentiated outcomes are particularly prevalent in such humanitarian settings, as women and girls risk physical and sexual attack, dehydration, injuries and exertion from walking long distances to fetch for fuelwood [32,41,62,137,155,156,228–230].

The dissemination and sustained use of clean cookstoves can have very positive humanitarian and development outcomes [108,162,165,169]. For example, in Kenya, the GIZ has managed over 20 years the local production and distribution of maendeleo portable fuelwood stoves to 68% of refugee households within Dadaab refugee camps [230].

4. Factors of adoption of clean bioenergy stoves in Kenya

4.1. Conceptual framework

The effective switch to clean and energy-efficient cookstoves depends on a set of factors that collectively affect stove acceptance, initial uptake, sustained use, maintenance and future replacement. Systematic reviews have identified various relevant factors related to stove characteristics, household characteristics, and the prevailing institutional landscape [8,145,234,235]. In Sections 4.2–4.8 we populate the conceptual framework of Puzzollo et al. [231] with literature from Kenya as systematised in Table 6.

To allow for a smoother discussion of the interactions between factors of adoption we follow a relatively different structure than Table 6, across the following domains:

- Fuel and cookstove characteristics (Section 4.2);
- Household and intra-household characteristics (Section 4.3);
- Knowledge and perceptions (Section 4.4);
- Financial mechanisms and subsidies (Section 4.5);
- Market development (Section 4.6);
- Policy coherence (Section 4.7);
- Regulation and standardization (Section 4.8).

4.2. Fuel and cookstove characteristics

Costs influence substantially the adoption and sustained use of stoves in Sub-Sahara Africa [118,170,233,275] and Kenya in particular [155]. As already discussed clean bioenergy stoves offer significant financial and time saving, as they require lower amounts of fuelwood (or even nullify the need for fuelwood) (Section 3.1).

The expected or actual lower operational costs and monetary savings often influence the decision to adopt improved bioenergy stoves, especially for those households that depend on buying fuel from markets (rather than collecting or producing it) [235,269,276,277]. On the other hand, fuel/cost savings are not an important factor of stove adoption for households that procure their fuel for free or at low costs, due to their proximity to forests [175,235,278]. Additionally, the expected time-savings can influence the adoption of stoves that consume less fuelwood and cook faster, especially by households that invest substantial amounts of time in fuel collection and procurement [107,274] Conversely, the opportunity costs of time spent on cooking or fuel collection may not influence stove adoption in setting where fuelwood and labor are abundant [148]. However, the high capital and maintenance costs of some types of clean bioenergy stoves such as biogas can become a barrier for the adoption of stoves by poor households [119,147].

Stove characteristics can also affect stove adoption and sustained use. For example, high time savings can be achieved through stoves whose materials and design allows for improved heat transfer, energy
efficiency and simultaneous cooking of different dishes [237,247]. In addition, stove designs that meet user needs and enable the preparation of local dishes with traditional cooking utensils are desirable in some local settings [113,116,119]. On the other hand, stove designs that fail to accommodate specific cooking styles, fuels, and available resources for maintenance and renovation might not be adopted in some local contexts [279]. Biogas systems are a prime example of how the above factors interact to influence stove adoption and sustained use. On the one hand, biogas systems can have substantial monetary savings from fuel purchase (about USD 0.40/m$^3$biogas) compared to conventional wood stoves [113]. Although the installation and capital costs are very high for poor households [119,279,280], the operating costs are often very minimal for household that have ready access to waste or animal dung for feedstock (e.g. livestock owners) [235,246]. However, as biogas systems are often marred with technical and operational difficulties [109,262,278], the proper training and reliable local support of users are essential for the adoption and sustained use of biogas systems [269,270].

4.3. Household and intra-household characteristics

Socioeconomic and demographic household characteristics such as size, income, education, and gender dynamics can influence decisions over the adoption of clean bioenergy stoves. For example, household income is a particularly important determinant of initial stove uptake [119,246], and becomes especially crucial when moving up the energy ladder, whereby the upfront stove cost increases (see above) [64,113,118,235,256,249]. Education often relates to knowledge and awareness about the perceived benefits of clean cooking [116,170,236,249] (see also Section 3).

On the other hand large household size can have a negative effect on stove adoption, as large households can share fuelwood collection and cooking among their members, thus assigning a lower value to the time and labor needed to perform such tasks [272,273,274]. Intra-household gender dynamics are also crucial for stove adoption, as households where women cannot make independent or consensual decisions over household budget allocation, might not prioritise stove purchase over other household needs [118]. Finally, home ownership (especially of permanent dwellings) may increase the willingness to invest in home appliances such as built-in stoves with chimneys [113,235,246]. Some technologies such as biogas systems require a spacious compound, strong land tenure, and ownership of at least 2–3 cows to provide a reliable source of fuel [148,237–239].

4.4. Knowledge and perceptions

Several studies in Kenya have highlighted a persistent lack of awareness on the available clean cooking alternatives and the consequences of cooking with traditional and inefficient stoves [100,138,239,281]. Enhancing public awareness and sensitizing the public about the health, safety, hygiene and environmental benefits of clean cooking is critical in catalysing the widespread adoption of clean bioenergy cookstoves [243,282]. However, some recent studies on consumer behaviour and stove choices have indicated a that strong focus on the health and climate mitigation benefits of clean bioenergy cookstoves does not influence substantially their adoption if they are not affordable [59,138,283–285]. In such contexts, stove promotion campaigns should prioritise messages that reflect the time and money savings, as such messages are more likely to boost the willingness to pay for clean bioenergy stoves [286]. Furthermore, combining techniques that forge social relations and facilitate behavioural change can influence the diffusion and adoption of clean cookstoves by creating social multiplier effects amongst peers [138,148,247,287–289]. However, the actual experience of the influencer can dictate the effect that social networks and peer influence can have either on stove adoption [46,234].

Cultural practices, traditions and beliefs can also enable (or act as a barrier to) stove adoption. For example, clean cookstove adoption can be hindered in cultural contexts where stove users use smoke as an insect-repellent, black soot for medicinal purposes or generally like the smoky taste of food [252]. In other cultural contexts the ability to accommodate the multiple utensils needed for cooking for large families

Table 6
Domains and individual factors of adoption of clean bioenergy stoves in Kenya [231].

Source: Domains adapted from [231].

<table>
<thead>
<tr>
<th>Domain/factor of adoption</th>
<th>Refs.</th>
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</thead>
<tbody>
<tr>
<td>1. Knowledge and perceptions</td>
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Note: NA denotes that it was not possible to identify relevant literature from Kenya.
or prepare local dishes with customized cooking utensils are pre-requisites for stove adoption [191].

4.5. Financial mechanisms and subsidies

Subsidies and financial incentives can influence significantly the initial acquisition of clean bioenergy stoves, especially if stoves are expensive or the potential users experience liquidity constraints [119,140,261]. However, large subsidies can have a negative affect on the perceived stove value, maintenance and future replacement [64]. Apart from financial incentives to low-income users, some studies have argued for offering subsidies in upstream activities in the stove value chain such as research, manufacturing, and distribution [252,259]. Similarly costs related to stove installation and maintenance (especially for stoves prone to malfunction and regular technical maintenance) may impede stove uptake and/or sustained use [100,272]. The availability of consumer finance through microcredit/loans, instalment payments options, price incentives and promotional offers can address to some extent such high upfront costs [101]. On the other hand, short repayment periods and high interest rates are significant barriers for obtaining microcredit/loans to purchase clean cookstove, especially for poorer households [243,259,287,290].

4.6. Market development

Stable markets, well-developed consumer strategies, and reliable supply chains can all have a positive effect for the adoption of clean stoves. Market development essentially increases marketing efficiency, distribution and sustained adoption of clean cookstoves [291]. However poor rural infrastructure can affect the distribution, accessibility, availability and pricing of stoves that are bulky, prone to malfunctions, and/or not locally produced [77]. To avoid such problems, organisations such as GIZ-Kenya, train local stove dealers and artisans to improve the accessibility, installation, maintenance and replacement of clean bioenergy stoves. These dealers also play an important role in raising local awareness and consumer education [233].

4.7. Policy coherence

Clean cookstove programmes ought to align their goals and complement the broader national energy policies (Section 2.2). Such coordinated efforts can mainstream clean cookstoves in existing and planned energy policies, thus creating a conducive policy environment to facilitate the widespread promotion and adoption of clean cookstoves [68,216].

The Government of Kenya has made several efforts to integrate cookstoves in existing energy policies, but not always in a coordinated manner (Section 2.2). One such recent effort (in 2016) has been the development of incentives to attract investments for scaling-up access to clean cooking, including the exemption of value added tax (VAT) on LPG. The Government of Kenya also announced the reduction of import duty on efficient cookstoves from 25% to 10% [80]. However, significant effort would be still needed to integrate more meaningfully cookstoves in the existing national energy policies (Section 5.2). For example, there must be coordinated action to link cookstoves with broader rural development programmes/policies and to foster greater community involvement [79].

4.8. Regulation and standardization

As already outlined in Section 2.3, very diverse clean bioenergy stove options are currently available in Kenya. It is very important to ensure the quality and performance of the available stove options to ensure both customer protection and trust [191] and ensure that proper incentives and market access is given to reputable stove manufacturers [30,100].

To ensure the quality of stoves introduced in the market, the Kenya Bureau of Standards (KEBS) developed household stove standards in 2005. However, these standards currently address only thermal efficiency, durability and the testing approach, but not the emissions of indoor air pollutants [292]. Moreover, enforcement mechanisms and penalties for non-compliance with the existing stove standards are yet to be formulated.

Currently, there are several stove-testing facilities at academic institutions (e.g. the University of Nairobi) and the Kenya Industrial Research and Development Institute (KIRDI). However, due to their high costs, many of the small local stove producers have limited access to these facilities [135].

5. Discussion

5.1. Knowledge synthesis

Section 4 outlined the very diverse social, economic, cultural, technical, organizational and personal factors that influence the initial adoption and sustained use of clean bioenergy cookstoves in Kenya. Some of these factors are more crucial for catalysing the initial household decision to adopt clean bioenergy stoves, while other factors
influence more decisions related to stove maintenance, consistent use, and future replacement. Fig. 4 illustrates the main linkages between these factors in Kenya.

On the demand-side (i.e. user-side), our review indicates that affordability, awareness and willingness to uptake a “better” cooking stove are key determinants of the initial purchase. Affordability depends on the socioeconomic status of households (i.e. purchasing power) and the availability of subsidies and economic incentives. However, the factors that motivate stove purchase, may not necessarily motivate its ultimate adoption and sustained use. Adoption and sustained use seem to depend much more on stove technology and design, and as an extension on the benefits expected to accrue from them. As already discussed in Section 2.3, there are several clean bioenergy stove options in Kenya, which have radically different technological and design characteristics (e.g. fuel use, time/financial investment, pollutant emissions) and ability to meet the various cultural requirement related to food taste and cooking multiple meals (Section 3).

On the supply-side, our review suggests that the stakeholders involved in stove promotion and dissemination can influence significantly stove adoption. This is because they can strategically influence the market in terms of stove accessibility, availability and affordability, through effective supply chain management, user engagement, demand creation, and provision of appropriate financial incentives and subsidies. That said, stove dissemination programmes and sales campaigns ought to ensure the readily available support for the maintenance and future replacement of stoves. Economic incentives to such stakeholders (e.g. reduced taxes and import duties) can create an enabling environment for further investments in clean cookstove value chains, and ultimately facilitate the diffusion of clean cooking technologies at affordable prices (Sections 4.5–4.6). To ensure that stove design and attributes meet user needs, expectations, and values, stove programmes must engage meaningfully the targeted stove users/communities (and particularly women) in stove design.

Stove adoption and sustained use can have multiple positive impacts for household energy security (Section 3.1), ecosystem conservation (Section 3.2), human health (Section 3.3), livelihoods (Section 3.4), education (Section 3.5), and food security (Section 3.6). Some of these impacts are gender-differentiated, so the adoption and sustained use of clean bioenergy cookstoves can provide an important impetus for female empowerment and gender equality (Section 3.7). Furthermore, clean bioenergy cookstoves can offer substantial benefits in humanitarian settings, reducing the multiple vulnerabilities that displaced groups face (Section 3.8). However, the widespread stove adoption can have some negative impacts, mainly through the loss of local livelihoods (Section 3.4). In order to minimise such negative impacts, such trade-offs must be taken into consideration by stove promotion policies and dissemination strategies.

It is worth mentioning that the type, mechanism and magnitude of these impacts can depend substantially on factors such as the: (a) stove technology and use patterns, (b) socioeconomic, environmental and cultural context within which stoves are promoted, (c) institutions that govern stove/fuel development, dissemination and use. Understanding the effect of these factors (and their interlinkages) would be crucial for informing the development and implementation of stove interventions that maximize the positive impacts of clean bioenergy stoves to humans and the environment.

### 5.2. Policy implications and future outlook for Kenya

Based on our literature review we identify six policy and practice domains that need to be targeted in order to achieve the effective promotion, adoption and sustained use of clean cooking interventions in Kenya. These include the need to: (a) adopt integrated policy approaches and enhance stakeholder collaboration, (b) raise awareness of the benefits of clean bioenergy cooking options, (c) facilitate access to funding and establish appropriate economic incentives, (d) implement quality assurance mechanisms, (e) facilitate behavioural change among stove users, (f) enhance research, development, and technical capacity.

Household cooking energy spans multiple policy domains (Sections 2.1–2.2) and several types of stakeholders (Section 2.3). Clean cooking policies and interventions should, to the extent possible, follow a multi-sectoral approach that integrates the perspective and interests of different government agencies with mandates ranging from energy, to agriculture, health, industry and the environment [191]. At the same time there is a need to enhance the role of local governments in the production and dissemination of stoves. It has been pointed that the lack of strong policy mandates at the level of the local government, may prevent the effective realisation of the clean cooking targets laid down in national energy policies [30] (see Section 2.2).

Overall, the lack of policy synergies, overlapping mandates and uncoordinated interactions with the private sector may lead to the suboptimal utilization of available resources and hamper stove production, financing, quality control, and scaling up [68]. Thus it is important to enable the development of a policy and regulatory environment that engages multiple stakeholders to actively regulate the clean stove sector, support innovation, attract investments, and enforce systems for non-compliance. Such a coordinated approach could maximize policy synergies and ensure that action plans are homogeneous and not operating in a compartmentalized manner.

Raising effectively consumer awareness about the availability and benefits of clean cookstoves is a key example of why a multi-stakeholder approach is needed. In the recent past, Kenya has successfully achieved market transformation and behavioural change for public health issues such as malaria (e.g. promotion of bed nets) and sanitation (e.g campaigns for hand-washing) [199,293]. However, when it comes to household energy use, many consumers are still not aware of the health risks associated with the use of traditional biomass and stoves [118,273,294]. Furthermore, consumer knowledge about the availability of different clean cooking alternatives is even more limited [128,239,281]. In order to enable behavioural change it is important to invest in educating (and raising the awareness of) consumers about the benefits of clean bioenergy stoves. This is a major undertaking that cannot be achieved by the private sector alone. Instead it will require the contribution of government agencies, international donors, research organisations and the civil society.

Access to finance is a key constraint across the clean stove value chain, especially as carbon finance markets weaken [252]. Evidence suggests that direct consumer subsidies may not be sustainable in the long-term, as income influences substantially the transition of households up the energy ladder [201,295,296]. However, direct subsidies linked to positive environmental and health impacts, or micro-financing, could enhance the affordability of stoves and fuels (and ultimately their long-term adoption) [100,211,297]. Flexible payment modalities for stoves and fuels, with longer payback periods, may also accelerate the adoption of clean bioenergy stoves [138,295]. At the same time, there is a need to rethink the taxes, import tariffs and trade barriers for stoves that are either imported or produced in Kenya by large international manufacturers. Lack of economic incentives to such players might preclude the extensive penetration of high-quality stove technologies or the manufacturing potential within Kenya.

Stove quality and high standards for energy services can also influence the adoption and sustained use of clean bioenergy stoves (Section 4.8). Whereas Kenya has made significant steps in formulating standards for biomass stoves [77], there is still a need to add provisions for emission reductions and enforcement mechanisms for non-compliance. When it comes to quality control, much more still needs to be done in Kenya, including long-term investment in testing centres that are not prohibitively expensive for local stove producers and artisans.

The transition towards universal clean cooking requires the radical transformation of the mindsets and cultural practices of stove users. Persuading users, mostly women, to stop using solid biomass requires tailoring policies and programmes to take account of the social and
cultural context of the targeted users. The active engagement of local communities, particularly women, is fundamental for stove design to help develop and deliver appropriate solutions tailored to local conditions and needs [242,251].

Finally, domestic stove producers have low technical capacity and manufacturing capabilities [100,201]. Major financing gaps prohibit market entry and the development of innovative products [30,298]. It is critical to develop mechanisms that can build the capacity for domestic stove production, assembly, marketing and financing. For example market intelligence is critical for the development of clean cooking options and is often highlighted as one of the biggest current technical constraints [16,148,252,266]. The scientific community can provide knowledge and practical solutions for these priority policy and practice domains. Our review is a first step towards integrating cohesively the current literature, but also identifies several research gaps that need to be targeted in future empirical studies.

First, we find that the existing knowledge about the impacts and adoption of clean bioenergy stoves is highly fragmented (Sections 3–4). We develop a conceptual framework that links the main phenomena at the interface of clean cookstoves adoption and impacts (Section 5.1) that should be tested in future empirical studies.

Second, despite some pockets of excellence there is a lack of high-quality empirical research about the performance, impacts and adoption dynamics of clean bioenergy stoves. To start with, there is a need to assess stove performance in realistic settings beyond laboratories. Such research will be important to understand the effects related to new clean stove models. Furthermore most current studies focus on single (or a limited subset of) impacts, drivers of adoptions, geographical settings and/or technologies. There is a need for more comprehensive quantitative studies that adopt a multi-impact assessment approach or a comparative outlook between different geographical, technological and sociocultural settings. Such evidence about the impacts and adoption dynamics is conspicuously missing in the existing literature for marginalised groups (e.g. refugees camps, humanitarian settings).

Third there is a need to involve more critically the perceptions/needs of stakeholders and the voices of users and local communities. For example participatory and ethnographic research approaches can involve more meaningfully local communities to elicit some of the cultural factors that might affect stove adoption and sustained use. The adoption of research co-design and co-production approaches could enhance the relevance of empirical research to the different stakeholder involved in clean stove value chains.

6. Conclusion

This literature review provided a comprehensive outlook of the current state of the clean bioenergy cookstove sector in Kenya. Clean bioenergy stoves can provide a sustainable solution in Kenya in the face of the increasing demand-supply imbalance of biomass energy, and the negative environmental and socioeconomic impacts of traditional cooking practices. We identify that a wide range of factors affects the adoption and sustained use of clean bioenergy stoves, including market structure, consumer awareness, stove design/quality, and the socio-economic status and cultural practices of stove users. Nonetheless, all these factors are highly interlinked and have varying degrees of importance depending on the environmental, socioeconomic and institutional context.

Overall, the adoption and sustained use of clean bioenergy stoves offers a practical solution to address many of the interconnected sustainability challenges that Kenya faces, from energy security/poverty, to public health, rural livelihoods, food security, education, women empowerment, and environmental conservation.

Although Kenya has been striving to modernise its energy system, clean bioenergy cookstoves are still not well integrated in current energy policies. Different stakeholders have undertaken several disjointed efforts to promote clean bioenergy stoves, with mixed, however, results. We identify six policy and practice domains that need to be targeted to enhance the sustainable development potential of clean bioenergy stoves in Kenya. These include the need to: (a) adopt integrated policy approaches and enhance stakeholder collaboration; (b) raise awareness of the benefits of clean bioenergy cooking options; (c) facilitate access to funding and establish appropriate economic incentives; (d) implement quality assurance mechanisms; (e) facilitate behavioural change among stove users; (f) enhance research, development, and technical capacity.

A deeper understanding of the interaction between the factors of stove adoption and stove impacts can provide a solid evidence base for developing policies and practical solutions to achieve universal clean cooking in Kenya, and elsewhere in Sub-Saharan Africa.

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