Article

Not peer-reviewed version

The Emergence of Large-Scale Bioethanol Utilities: Accelerating the Energy Transition for Cooking

Helen Hoka Osiolo * , Hanaan Marwah , Matthew Leach

Posted Date: 11 August 2023

doi: 10.20944/preprints202308.0884.v1

Keywords: bioethanol; clean cooking; KOKO Networks; environmental and social impact; SDG7; utilities, scalability

Article

The Emergence of Large-Scale Bioethanol Utilities: Accelerating the Energy Transition for Cooking

Helen Osiolo [1,*], Hanaan Marwah [2] and Matthew Leach [3]

[1] Modern Energy Cooking Services programme, Loughborough University, Loughborough LE11 3TU UK; H.H.Osiolo@lboro.ac.uk
[2] KOKO Networks, Rivaan Center, Nairobi, Kenya; h.marwah@kokonetworks.com
[3] Gamos Ltd., 231 Kings Rd, Reading RG1 4LS, UK; profmattleach@gmail.com
* Correspondence: H.H.Osiolo@lboro.ac.uk

Abstract: The use of bioethanol in cooking is not new, but until recently its application has been confined exclusively to small scale projects. However, a new bioethanol cooking utility in Kenya has now reached mass market adoption, serving more than 950,000 households with cooking fuel since launching in late 2019. Its success was made possible by a significant investment in technology to facilitate safe, convenient and affordable fuel distribution. It is funded by climate finance which is based on bioethanol fuel replacing charcoal used for cooking, a leading cause of African deforestation. This development has been so recent that it has not widely been discussed in the academic literature. More broadly, the health, environmental and economic impacts of bioethanol for cooking have not been systematically assembled in one place. This article details what is known about the impact of bioethanol for cooking, how and why bioethanol for cooking was able to suddenly reach commercially viable scale in spite of the challenges it faced. It also discusses implications for further scaling of clean cooking fuel solutions.

Keywords: bioethanol; clean cooking; KOKO Networks; environmental and social impact; SDG7; utilities; scalability

1. Introduction

Despite research and policy initiatives targeting the challenges of clean cooking access and the significance of new strategies to attain SDG 7, government funding available for clean cooking objectives in many countries is still a small fraction of funding for electricity access [1]. In sub–Saharan Africa the population without clean cooking access continues to rise [2]. It is widely acknowledged among the development community and national governments that the private sector will need to play a pivotal role in addressing the issue to accelerate a clean energy transition. However, except for prominent oil and gas companies in a few African markets, most private sector clean cooking companies continue to operate on a small scale. These small yet innovative companies concentrating on cooking solutions have received support from a variety of results-based finance and technical assistance programs such as the Clean Cooking Alliance Venture Program, but only a few of them have a customer base exceeding a few thousand households. Furthermore, many of these clean cooking companies sell solutions which use fuel that fails to meet the definition of clean cooking as outlined by the WHO's guidelines on indoor air quality and the standards of SDG7.

However, over the course of 2014-2023, a new clean cooking fuel utility business model based on the biofuel bioethanol was developed by a private company in Kenya using a combination of new technology and climate finance. The growth has been unprecedented for the sector. Within 2.5 years of the customer launch date bioethanol was being used for cooking by over 950,000 household users, impacting an estimated 3.7 million people, under the brand KOKO Networks (KOKO). This rapid large-scale introduction and adoption of a new cooking fuel has typically only occurred with large government subsidy programs such as those for Liquid Petroleum Gas (LPG) adoption, and other recent government schemes to encourage electric cooking. This was a result of years of private sector research and development, investment, and trial and error. Bioethanol has been identified by the academic literature and in the development community as a promising clean fuel to replace charcoal but until now has never been commercialised. Its recent large-scale adoption motivates a review of evidence about the potential positive impact of bioethanol and potential implications for research and policy.

This article aims to (i) explore the published academic data on the various health, environmental and economic impacts of bioethanol fuel and stove technology for cooking; (ii) apply the MECS transition theory of change (TToC) to bioethanol cooking to explore expected current and future barriers to scalability, and (iii) examine in detail the KOKO bioethanol utility growth and the challenges it faced and overcame in light of the MECS TToC model and (iv) draw out implications of this analysis for further scaling of modern energy clean cooking.

2. Bioethanol for cooking literature review

Bioethanol is among the few fuels for cooking that have the potential for positive health [3], climate and environmental [4], gender equality [5], increased employment opportunity, earnings, time and fuel saving [6] impacts alongside other wider economic and welfare implications. However, despite this wide range of known benefits, until recently bioethanol has remained relatively unexplored by researchers and policymakers. According to [7], writing before the launch of KOKO in Kenya in late 2019, bioethanol is the least appreciated clean fuel today in most developing countries, and received the least amount of attention, despite its performance attributes when compared to LPG. There have been few comprehensive impact analyses of bioethanol alongside other fuels and stove technologies for cooking. This is explained by the limited number of studies that have taken place and a lack of consensus on approach. The absence of rigorous analysis of the benefits, as well as of the historical barriers to scalability, currently limits the understanding of the potential contribution of bioethanol fuels and stove technologies for cooking.

Globally recognized approaches to estimating the impacts of fuel and stove technologies are lacking and largely segregated focusing on one or two specific impacts (i.e., health, environment, or wider economic impacts). A detailed review of the approaches used to estimate the impacts of cooking more generally are outside the scope of the current paper. The focus here is on the empirical evidence available and outcomes of related benefits analysis.

The most extensive evidence on improved and/or clean fuels and stove technologies for cooking is in household transitions from using solid biomass (including firewood and charcoal) in traditional stoves to improved fuels and stove technologies [3,8–10]. More recent studies focus on transition to modern/clean cooking fuels such as LPG, biogas, and electricity [5,11]. Bioethanol is one of the cooking fuels considered to be clean based on the 2014 WHO guidelines, which aim to reduce health risks associated with exposure to indoor air pollution from household fuel combustion. Within the World Bank's the Multi-Tier Framework for cooking [12], within which improving performance attributes across local emissions, efficiency, convenience, safety, affordability, quality and fuel availability leads to higher tiers, bioethanol qualifies as a tier 5 (i.e., top) clean fuel and technology.

This section discusses the evidence around bioethanol cooking organised by three impact categories: health, climate and environment, and economic and opportunity costs. It also provides a summary of how bioethanol supports achievement of a range of SDGs.

2.1. Health impacts

This section explores the evidence on health benefits of using bioethanol for cooking. The discussion highlights the health illness/diseases that may emanate from using non-clean fuels and stoves and the possibilities of health improvement if any switching happens; to use clean fuels and stoves for cooking such as bioethanol.

Cooking with open fires has harmful effects on health due to both Household Air Pollution (HAP) and the physical effects of fuel collection. HAP causes or exacerbates a wide range of conditions, including ischaemic heart disease (IHD), stroke, lung cancer, chronic obtrusive pulmonary disease (COPD) for adults, and acute lower respiratory infection (ALRI) for children [3,8,13], with greater risk among the poor population [14]. Additionally, because of women's role in cooking and caring for children they are highly exposed to the pollutants/particles produced from incomplete combustion, which leads to respiratory and eye disorders with a high incidence of death approximated at 1.6 million/year [15].

There is growing consensus that use of improved stoves with the same solid biomass fuels does not significantly reduce the negative health effects associated with open fire cooking. For example, [9] provided evidence of this, while showing that the use of other cleaner fuels (i.e., LPG, bioethanol and biogas) offers greater health benefits.

Due to the few studies that have been carried out and the time it takes for studies to get funding etc, since bioethanol has been commercialised at scale, empirical evidence for the health benefits of bioethanol-fuelled cookstoves specifically is still relatively scarce. However, [16] and [17] both show that cooking with bioethanol is a cleaner and healthier alternative and [15] include it as one of the options for an improved health condition delivered from cooking with a clean smokeless fuel.

In Ethiopia, [18] investigated the impact on indoor pollutants of using an bioethanol stove instead of inefficient cooking with wood. In their study wood is associated with two major pollutants; Soot/particulate matter (PM2.5) and carbon monoxide (CO) which are responsible for the bulk of the negative health impacts of indoor smoke. [18] and others show that the use of bioethanol stoves resulted in average reductions of 84% and 76% for PM2.5 and CO, respectively.

Other health impacts have been studied showing the implications of bioethanol for cooking and pregnancy. Recent evidence from Nigeria shows that switching to bioethanol-fuelled stoves has the potential to provide needed protection for women and their developing foetus [19].

[7] report on their own literature review of the emissions by different cooking fuel (firewood, charcoal, kerosene, LPG, and bioethanol), and conclude that bioethanol and LPG offer the greatest, and broadly comparable, health benefits.

A separate type of health benefit arises for a switch away from firewood, with reduction in the need to carry wood long distances [20]. Health effects of wood collection include long-term physical damage on the backbone, head, hands, and legs from the strenuous work [21] as well as wild animals and snake encounters.

2.2. Environmental impacts

Environmental impacts of cooking discussed in this section includes greenhouse gases and carbon neutrality, indoor and outdoor air pollution, biodegradability, deforestation, and the provision of warmth. At the end of this section, the health and climate impacts of cooking with different fuels and stoves is briefly summarised.

Burning bioethanol is widely assessed to be a carbon neutral activity, in the sense that the amount of carbon dioxide that is emitted during combustion is the same amount by the plants during photosynthesis for growth [13]. [9] show that use of other cleaner fuels (i.e., LPG and biogas) offer lower greenhouse gas (GHG) emission reductions. Bioethanol emissions with sugarcane bagasse as a feedstock can meet the European Union Renewable Energy Directive of 60% reduction in GHG emissions relative to petrol and other agricultural and forest sources [10]. In terms of air pollution beyond being associated with reduction in indoor air pollution, bioethanol is also associated with improved outdoor air quality [13]. In terms of impacts on other media, Bioethanol is considered biodegradable, so reducing toxic impacts of potential fuel spillage on land and in aquatic environments [22].

Empirical evidence shows that charcoal sold in urban areas and rural wood gathering contribute significantly to deforestation [23]. Deforestation in turn can lead to deforestation and aridification [24]. According to [15] using a carbon-neutral source such as bioethanol and/or a more efficient combustion process means that forest degradation can be halted and reversed, and tree cover has a chance to regenerate. There are significant emissions reductions from a household switching from burning charcoal for cooking to bioethanol.

Finally, bioethanol burns cleanly enough that a chimney is not needed to remove air pollutants from an indoor kitchen. As such the heat generated is retained in the room, which is a benefit in regions or at times of the year in which space heating is wanted.

The interlinkages between the act of cooking using fuels and stove technologies and the consequences it has on health and climate is evident. Figure 1 presents an overall scoping of health and climate impacts for a wide range of fuel and stoves combinations warn these are averages and actual performance varies widely. However, bioethanol is included in region 4, with the least health and climate implications, which is a cluster of the modern renewable fuels including bioethanol (a liquid), and biogas [3].

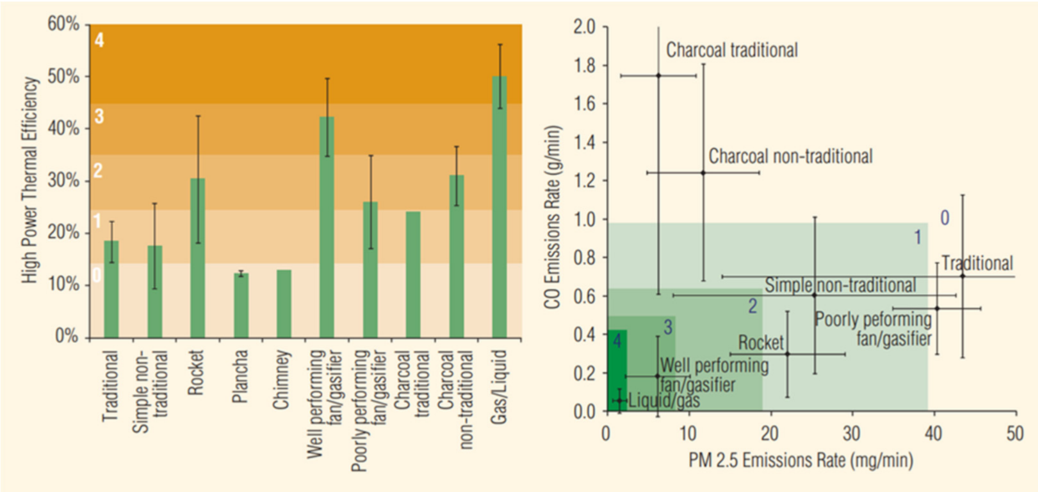

Figure 1. Health impact and climate impact of cooking technologies. Source: [25].

2.3. Economic and opportunity cost impacts

Switching to using clean and modern energy sources for cooking has benefits beyond health and environment, including a wide range of economic and opportunities costs. These include job creation, gender equality/balance and reduced inequalities, reducing rural poverty, enhancing energy security while at the same time reducing dependency on imported fossil fuels and associated demand for foreign reserves, and wider economic sector growth (e.g., in agriculture productivity and food security).

Evidence shows women face disproportionate burden from societal roles which expect women to collect fuel, prepare and cook food [13]. [5] identify the following implications of use of bioethanol for gender equality: first in terms of time saving that would be instead spent in fuel collection; second, the freed up time offers women opportunity to engage in income generation, education or leisure activities [13]; third, exposure reduction to HAP and related illness; and fourth, time and fuel savings resulting from bioethanol for cooking (ECF) technology that is efficient and has higher energy concentration compared to other fuels. Generally, in a day women and children spend 4.5 hours on unpaid work [26].

There has been a historical concern about bioethanol production and its potential implications for food security, environmental degradation and water profligacy, however this has been comprehensively disproven in the academic literature [27,28]. Instead, where bioethanol cooking fuel is replacing charcoal, which itself is the main cause of deforestation and desertification of land, as well as a major local cause of death from household air pollution, there are very significant local benefits to a fuel switch and may have major positive implications for poverty alleviation and food security if a local bioethanol industry can attract investment into agricultural processing.

In Kenya the government, through its bioethanol cooking master plan, has seen the development of a local bioethanol cooking industry as valuable for economic development as well as for social and environmental impact, and as it can be derived from attracting more investment into the local existing sugar industry, is not a concern regarding food security or land use. South Africa in contrast has deployed a legislative reach, restricted production to needs of local market and requiring registration of producers for fuel tax rebates [29]. Rather than threatening food security, Cartwright in his study concludes that there is probability that investment in Southern African Development Community

(SADC) rural economies could enhance food security, through the provision of infrastructure, the transfer of skills, the supply of animal feed by-products and the reduced exposure to oil driven food price inflation.

Table 1 compares the impact estimates of using bioethanol fuel and stove technology for cooking with that of biomass, at the household, national and sub-Saharan Africa in general. Comprehensive impact estimates including those that focus on monetary values for both fuel and stove cooking technologies are limited and are less well developed for modern and clean fuel and stove options such as bioethanol [7]. Thus, possibilities of underestimating the health, environment, and wider economic impacts remain a concern that affects policy discussions on clean cooking transitions globally.

Table 1. Impact estimates of using bioethanol fuel and stove technology for cooking.

Impact category	At national level (Kenya) Biomass	At Household Level (Kenya) Bioethanol	At national level (Kenya) Bioethanol	Sub-Saharan Africa Solid Fuels[a]
Environmental	• Deforestation and forest degradation: Kenya loses 10.3 million m3 of wood from its forests every year from unsustainable charcoal and wood fuel use [c,e] • A major contributor to the 0.3% per year deforestation rate[e] • GHG emissions: Household fuel use in Kenya contributes 22-35 million tonnes of CO2 eq. each year, (equivalent to 30-40% of total Kenya GHG emissions) [c,e]	• Up to 30 trees saved per HH annually from switching from charcoal[e] • Slows down rate of deforestation and, consequently, its impact on food insecurity[e] • 0.7-5.4 tonne reduction in GHG emissions per HH per year from switching from kerosene and charcoal respectively[e]	• Deforestation averted: Up to 54 million trees saved[c] • GHG emissions: Up to 13.5 billion kgs of C02 equivalent saved[c]	• Total Environment in billion USD: low ($0.6), mid ($6.3) and high ($11.9)[f] • GHG emissions (fuel consumption) in billion USD: low ($0.2), mid ($2.1) and high ($3.9)[f] • GHG emissions (charcoal production) in billion USD: low ($0.2), mid ($0.7) and high ($1.2)[f] • Deforestation in billion USD: low ($0.2), mid ($3.5) and high ($6.7)[f]
Health	• Indoor air pollution: 728k Disability-Adjusted Life Years (DALYs) and 16.6k deaths annually[e] • 8-10% of early deaths in Kenya[c,e] • Lower respiratory tract disease is the third largest contributor of deaths in Kenya [e] • Pneumonia is a major cause of	• ~0.25 DALYs saved per HH per three-year intervention period from switching from charcoal and kerosene [e] • Reduction of ~50 deaths per 25,000 households from reduced indoor air pollution [e] • Safety risks of storage, handling and use are lower	• Disability-adjusted Life Years (DALYs) averted: Up to 507,000 DALYs [c] • Deaths averted: ~3,700 deaths could be averted [c] • Economic value of deaths averted and DALYs saved: ~KES 372 million in lost wages [c]	• Total health in billion USD: low ($0.6), mid ($0.8) and high ($1.5) [f] • Mortality from household air pollution in billion USD: low ($0.3), mid ($3.5) and high ($6.8) [f] • Morbidity from household air pollution in billion USD: low ($0.2), mid ($0.7) and high ($1.1) [f] • Other health conditions (burns, eye

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 August 2023 doi:10.20944/preprints202308.0884.v1

	death to children under the age of five, largely due to indoor air pollution [e]	for a liquid than pressurized gas [e]		problems in billion USD: low ($0.1), mid ($0.8) and high ($1.5)[f]
Economic/ Opportunity costs	• Food insecurity: deforestation, resulting from the use of dirty fuels, exacerbates food insecurity and harms the agriculture sector [c,e] • Foregone incomes for avoidable time spent cooking and cleaning [c,e] • Avoidable spending on expensive fuel [e] • Tax revenue loss for government given informality of market [e]	• Distributed in smaller volumes, making it more accessible to lower income users [e] • Existing domestic bioethanol sector could be expanded, creating formal, taxable jobs and boosting smallholder farming income [e] • 20-40 mins saved per HH per day from switching away from charcoal [e]	• Jobs created: Up to 370,000 jobs (with the majority in feedstock production) [c] • New income generated: Up to KES 51 billion, with additional income of up to KES 180,000 per year for smallholder farmers [c] • Increased demand in the agricultural sector to produce fuel from agricultural residues and wastes [d] • New opportunities for value-added investment in the agricultural sector [d] • Greater financial resources and boosted GDP from reduced fossil fuel imports and demand for foreign earnings and guarantees security of energy supply [d,c]	• Total economic in billion USD: low ($4.2), mid ($20.6) and high ($36.9) [f] • Spending on solid fuels in billion USD: low ($0.4), mid ($3.8) and high ($7.3) [f] • Time wastage (fuel collection) in billion USD: low ($0.6), mid ($6.5) and high ($12.4) [f] • Time wastage (cooking) in billion USD: low ($3.3), mid ($10.2) and high ($17.2)

a annual economic losses and opportunity costs associated with solid fuel dependencies in Sub-Saharan Africa (in billion USD). b high possibilities of underestimation of the full disease burden as many negative cooking health effects have not yet been quantified (e.g., burns, eye diseases, physical injuries from carrying firewood, etc.). c [5]. d [13]. e [7]. f [6].

2.4. Contribution to SDGs

Using bioethanol for cooking supports several Sustainable Development Goals, briefly presented in Table 2.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 August 2023 doi:10.20944/preprints202308.0884.v1

Table 2. Bioethanol for cooking and its contribution to SDGS.

SDGs	Bioethanol for cooking contributions
SDG 1: No Poverty	Saved time resulting from cooking with bioethanol can be spent on income generating activities [13]. Potential for cheaper fuel using discounts from carbon credits generated from fuel switch (KOKO model). Potential for additional income for small shopkeepers from fuel bioethanol fuel dispensing machines. Potential to support farmer incomes from locally sourced fuel
SDG 2: No Hunger	Investing in bioethanol industry enhances agricultural productivity and food security [29,30]
SDG 3: Good Health and Well Being	Switching from using wood and other biomass fuels to use bioethanol for cooking Improves health conditions through reduction in exposure of both PM2.5 and CO [13,30]
SDG 4: Quality Education	Using bioethanol instead of traditional biomass can help children, especially girls, stay in school by reducing time spent on cooking and collecting fuel for the household [13,30]
SDG 5: Gender Equality	The saved time as a result of bioethanol for cooking instead of traditional biomass, reduces the burden of unpaid care work especially among women, which remains a major cause of gender inequality [13,30]. Additional potential impact from the ability to move to two burners stoves
SDG 7: Affordable and clean energy	The ability of bioethanol to be distributed in even smaller volumes enhances accessibility and affordability of bioethanol fuel, especially among the lower income population [13]
SDG 8: Decent Work and Economic Growth	Demand for bioethanol for cooking spurs employment generation beyond bioethanol processing plants, distilleries, and distribution to other sectors and enhances overall economic growth [13,30]
SDG 9: Industry, innovation and infrastructure	Development of bioethanol industry will require innovations in bioethanol production introduces innovative farming practices and agricultural zoning research. A clear concept for supply chain, involving local stakeholders from an early planning stage, supports several intersecting industries [30]. Bioethanol for cooking requires investment in technology (hardware and software), storage and transportation infrastructure.
SDG 10 – Reduced inequalities	Saved time associated with bioethanol for cooking, reduces inequalities represented in form of reduced time spent on income generation, education or leisure activities [13]
SDG 11: Sustainable Cities and Communities	Clean cooking addresses household and ambient air pollution, resource efficiency, and climate vulnerability [13]
SDG 12 – responsible consumption and production	Sustainable bioenergy production helps to prevent deforestation. Careful planning conserves environmentally sensitive areas, making use of rehabilitating abandoned, intensively use farmland or moderately degraded land [30]
SDG 13: Climate Action	Bioenergy supports resilience against climate change. Bioethanol replaces fossil fuel and traditional biomass, reducing greenhouse gas emissions [13,30]
SDG 15: Life on Land	Bioethanol for cooking reduces the amount of wood required for cooking, thereby reducing environmental degradation and pressure on forest resources [13] Bioethanol is carbon neutral/biodegradable since the amount of carbon dioxide that is emitted during combustion is almost equal to the amount of carbon dioxide absorbed by the plants during photosynthesis for growth [30]

3. Materials and Methods: understanding barriers to scalability of bioethanol fuels and stove technologies for cooking

Historically, increasing adoption and use of clean and modern cooking technologies in Sub-Saharan Africa has been hampered by a range of factors, including poverty, stove functionality, stove design, fuel availability/accessibility, fuel costs/affordability, awareness [31], and relatively high cost due to unfavourable tax and tariff treatment relative to cooking fuel alternatives like charcoal, kerosene, and LPG [7,30,32]. The potential impact of bioethanol cooking has made it attractive for a number of clean cooking companies and development institutions. However, until the explosive growth of the KOKO business model, many of the same barriers to scale have held back the growth of the industry.

The barriers to bioethanol fuel and stove technologies for cooking discussed here are based on the Modern Energy Cooking Services (MECS) transition theory of change (TToC) for cooking adoption, which consists of three interrelated dimensions [1].

The first is addressing **consumer preferences and demand creation**. Specifically for bioethanol, which offers consumers a similar cooking experience to gas, lack of awareness has been a barrier. According to [3] and [7], success of clean cooking programs in developing countries is possible by prioritising accelerating awareness creation.

The second dimension is a **robust and commercially viable supply chain and delivery model**. A hindrance to scale-up of bioethanol programmes has been the lack of access to business and startup finance to access the cookstove technology [6]. It also requires technology from the production and collection of sufficient raw material, its purchase at a fair price, to its conversion into a final product that is attractive enough to be sold in a competitive market and meet local requirements. Feedstock availability and sizing market demand for bioethanol over the entire project duration is also a consideration [30].

The third dimension is the **enabling environment and policy**. Without enabling policy, standards and a regulatory environment [6], companies face implementation challenges. According to [30] bioethanol cooking fuel faces a lack of policy support as most governments are unaware of the of their economic, social and environmental benefits. They even face some unfair competition in relation to technologies using subsidised fossil fuels.

KOKO in Kenya managed to overcome most of these barriers through a long process of addressing each one over a series of years, which gives confidence to the sector that these historical challenges can be overcome. By exploring KOKO's development using this structured theory of change, lessons can be learnt for the benefit of the wider clean cooking sector, contributing to the achievement of SDG7. The following tells the story of KOKO's development, set against the broad structure of the MECS TToC; further detailed analysis is provided in the appendix.

4. Results: the emergence of large-scale bioethanol cooking in East Africa

4.1. Commercial Pilot: CleanStar Mozambique

The founding investor in KOKO, CleanStar Ventures, also made a founding investment in 2010 in a predecessor "Commercial Pilot" venture, CleanStar Mozambique.

Bioethanol had been identified by the investors in CleanStar Ventures as a promising potential solution to tackle the prohibitively high prices of clean fuels for cooking. Crucially, bioethanol held the potential to significantly reduce the rate of deforestation in sub–Saharan Africa, where charcoal is the primary cause of deforestation, while eliminating the negative consequences of cooking with biomass fuels on health, gender inequality and economic productivity. This is well positioned with the second TToC dimension, as bioethanol advances into sustainable fuels supply. Bioethanol can be locally produced in many countries, creating a beneficial supply chain which can provide income to historically underinvested agricultural communities. It can also be imported at scale from the large and cost-effective bioethanol industries in the US, Brazil and India, lending important security of supply for consumers, essential for a cooking fuel utility. Critically, as a liquid fuel, it can be transported and stored using the same liquid fuel infrastructure as petrol and diesel, which already exists worldwide even in remote and rural areas, unlike compressed gas fuel infrastructure needed for LPG which is costly to build. Bioethanol for cooking, thus addresses the first and third TToc dimensions, where through development of the bioethanol industry leads to job and income generation, provides security of fuel supply, and allows easy transportation and storage of fuel respectively. For consumers, with the right stove and canister, cooking with bioethanol is the same experience as cooking with gas, but safer. This supports the first dimension of the TToC. Bioethanol fuel can replace cooking with biomass or fossil fuels entirely and is an attainable major step in the zero fossil fuel energy transition.

CleanStar Mozambique's commercial pilot was involved in the full bioethanol cooking supply chain from buying feedstock from farmers, small-scale bioethanol production, and selling fuel and bioethanol stoves through small shops. The venture was successful on a number of fronts: it aligned with key policy drivers, and it demonstrated user acceptance of the bioethanol cooking experience at a wider scale than had been demonstrated previously (reaching 35,000 households within one year). This aligns well with the first and third dimensions of the TToC. The pilot also showed that climate finance could be used to fund the bioethanol cooking business model, aligning with part of the second dimension of the TToC. However, the key commercial discoveries were that the "centralised bottling" method of distribution of bioethanol was not financially viable and in the view of the management, unsafe for consumers if scaled up to millions of households. Thus, key aspects of the Supply Chain and delivery model dimension of the TToC were unresolved and constituted a serious blocker on further scaling.

4.2. Development of new cooking fuel distribution technology

CleanStar Ventures then set out to develop the technology platform to overcome the commercial challenges of household bioethanol distribution. They established a new venture, KOKO Networks, and hired a team of engineers who invested five years, 2014 through 2019, developing new hardware and software technology in Nairobi and Kampala, to prepare a launch of a new bioethanol fuel utility model which overcame the structural challenges of the centralised bottling mode of bioethanol cooking fuel distribution. Inspired by milk-dispensing 'ATM' machines used in India, they saw dispensing machines based in small neighbourhood corner shops as an alternative distribution method to selling bottles of fuel and the significant safety hazards of an open bioethanol supply chain. Their prototypes had not only high-tech dispensing machines, which used mobile money and an identifying chip in the sealed reusable fuel canister, but in also three additional unique pieces of technology hardware: a 'smart' filling system at a petrol station and a 'smart' sensor on top of a micro-tanker fuel truck which does the refilling of dispensing machines. At each stage the fuel temperature and surrounding vapour is checked regularly by the machines for any leaks, spills or tampering, reporting back data remotely via a cloud-based monitoring system. The system is run as a fuel utility with most dispensing machines refuelled every day by a fleet of micro-tankers which are dispatched from a Network Operations Centre (NOC) which uses software and a 24-hour monitoring team to minimise any system or fuel 'downtime'.

However, it was not only the technology and systems which needed to be developed before the utility could be launched, other elements of the 'jigsaw' puzzle composing the supply chain [1] needed to be in place. Hardware and fuel standards to establish safety for consumers needed to be drafted and agreed with the Kenya Bureau of Standards before it launched in Kenya, its first consumer market. These standards and regulatory protocols included the calibration of the dispensing machine, the bioethanol cooking stove, the requirement to colour and denature the bioethanol so that it could not be accidentally ingested, and testing of each bioethanol batch.

Another important jigsaw puzzle piece for the Supply Chain was long term access to storage infrastructure to transport and store bioethanol to enable dispensing to consumers needed to be secured. KOKO signed a long-term agreement with Vivo Energy, which owns petrol stations across 23 African countries under the brand names of Shell and Engen, to use storage tanks under conveniently located petrol stations.

It was also important that other jigsaw puzzle pieces of the Enabling Environment were aligned, notably that regulation of the sector fit into government policy. In addition to the existing government

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 August 2023 doi:10.20944/preprints202308.0884.v1

bioenergy strategy, which already included the potential for bioethanol cooking, the Kenyan government, with support from the Government of Germany, commissioned a national bioethanol cooking master plan, which was completed in June 2021, and involved broad consultation both inside and outside of government [33].

4.3. Innovations in climate finance

The company was designed to be financed through the sale of carbon credits into regulatory markets. KOKO earns carbon credits based on customers switching to bioethanol for cooking from using non-renewable biomass (charcoal and firewood) which would otherwise cause deforestation. Its carbon credits from 2020 were verified under the UNFCCC CDM, and sold to meet South Korean corporate regulatory carbon offsetting requirements. The price of both stoves and fuel were heavily discounted using the intended future sale of carbon credits and carbon pre-finance secured by the company. After the changes to the global carbon compliance market mechanisms from 2021, KOKO began marketing its credits to the voluntary carbon markets through its carbon marketing team based in London. The current and expected future price of carbon credits will be important for the company's future growth as more rural customers will need lower prices to make bioethanol affordable for cooking compared to cheaper firewood as compared to charcoal. The higher carbon prices are, the more KOKO can lower fuel prices for its customers.

4.4. Challenges and growth

By the time the new cooking fuel utility was ready for its customer launch in December 2019, the company already had approximately 500 staff, an inhouse manufacturing facility and a network operations centre, ready to be a fully functioning, though initially small-scale fuel distribution utility. The first major hurdle the company faced was the COVID-19 pandemic in early 2020, when the company had approximately 20,000 customers. Apart from operating challenges of lockdowns, social distancing and staff illness, sudden international and local shortages of bioethanol which were needed for hand sanitizer caused initial supply issues. These issues did not settle until the beginning of 2021, after which the growth of the utility was exponential. The company reached the 100,000-customer milestone in March 2021, 200,000 by August of the same year, 500,000 by June 2022, 850,000 by March 2023 and 950,000 by June 2023 spread across eight cities and towns around Kenya. The network of dispensing machines grew in tandem with the customer base, reaching 2,000 machines in early 2023. In 2022 KOKO signed an investment agreement with the Government of Rwanda to launch a nationwide bioethanol cooking fuel utility and plans to launch there later in 2023.

Customer acceptance of the product was driven by the 'gas-like' rapid, modern and convenient cooking experience that users aspired to but could otherwise not afford, and the affordable price point of the fuel which was generally 30-40% cheaper than charcoal. A two-burner stove as standard decreases meal preparation time, and the fuel dispensing machines are strategically designed to be a 5-minute walk from customer homes. Adoption of cooking with KOKO has been quicker in each subsequent city launch in Kenya after Nairobi, presumably because of the widespread brand awareness of KOKO and its products in Kenya.

The proposition is designed to satisfy key elements of Customer Demand, and to do so with a scalable Supply Chain and Delivery Model, with care taken to align with the range of requirements comprising the Enabling Environment.

5. Discussion and Conclusions

5.1. Implications for policy: the potential for fuel switch from bioethanol adoption

In many countries the lack of an alternative to unaffordable LPG subsidies to enable clean cooking fuel adoption has resulted in continued use of programs to distribute the so-called 'Improved Cook Stoves' (ICS). Through significant investment in technology and funding from climate finance, KOKO have been successful in starting to scale bioethanol for cooking. Support from climate finance makes the solution affordable even for non-urban customers over time.

The demonstrable benefits for forest protection and health, contributions to economic gains in African countries, alongside support for 13 SDGs, suggests that the bioethanol cooking fuel utility should be explicitly considered in energy access, forest protection and climate finance policy, alongside other modern energy cooking options, notably electricity and biogas. Large scale bioethanol use can accelerate affordability, minimise charcoal use and prevent deforestation and its impact on soil quality. With careful planning to protect food production, and rapid adoption of relevant standards and regulation, local large scale sustainable bioethanol production and associated supply chains will be developed, stimulating jobs and local economic development. The characteristics of the fuel itself are important for the benefits achieved, but so too is the design of the customer-facing fuelling infrastructure, as also found by [34].

Given that climate finance so far is explicitly available for the bioethanol cooking model because of its impact on forest protection, the model is suitable for countries with high rates of deforestation or those which have other sources of funding other than climate finance, such as a government or donor subsidy program. The enabling policy environment for a bioethanol fuel utility also requires minimising taxation - excise duty, Value Added Tax (VAT), import duty - to enable affordability for target households currently reliant on the cheapest fuels available.

5.2. Lessons from the transition theory of change

Historically, barriers to wider adoption and use of bioethanol for cooking have included lack of access to finance, fuel availability and affordability, meeting local demands (stove functionality and design), awareness, enabling policy, standards, and a regulatory environment.

While the success of KOKO as a business, and the success of its cooking fuel utility offering, have many origins, careful attention to aspects that fall within the three dimensions of the MECS TToC are key. A clear proposition of lower costs drives Consumer Demand. However, this demand is reinforced by the Supply Chain and Delivery Model, which is both scalable for the business, but also delivers customer convenience. Finally, careful attention to the Enabling Environment, including deforestation and climate policy drivers, but also spanning health and safety was crucial.

Finding technical solutions, both in fuel type and delivery infrastructure, that ticked all these boxes has enabled rapid scaling (as presented in the Appendix Table A1).

Author Contributions: Conceptualization, H.O. and M.L. Methodology development, H.O. and M.L . Formal analysis and Investigation, M.L., H.M. and H.O.; Validation and Visualization, led by M.L., supported by H.M. and H.O. Writing - original draft preparation, H.O. and H.M.; writing - review and editing, H.M., M.L. and H.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded under the UKAid-funded programme, Modern Energy Cooking Services (MECS) (GB-GOV-1-300123).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy and confidentiality concerns.

Acknowledgments: We thank our stakeholders and MECS programme partners for supporting the research for this article. .

Conflicts of Interest: The authors declare no conflict of interest, but wish to note that H.M. is an employee of KOKO Networks.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 August 2023 doi:10.20944/preprints202308.0884.v1

Appendix A

Table A1. MECS TToC framework barriers to scale up bioethanol fuel and stove technologies for cooking, including the KOKO experience.

Barriers/Success/Scale-up Factors	KOKO experience	Theoretical recommendations for bioethanol cooking scale up
Stove & fuel technology	KOKO spent 5 years developing and patenting its own stove and fuel distribution technology and has continued to issue improved versions based on customer feedback	• Ensure on-going development of technologies is in response to customer feedback and competition to address efficiency and affordability of cookstove technologies [6,35] • Need to tap local innovation where research and development in the local cookstoves sector is promoted to match the support (finance and policy access) that larger, international cookstove partners can access [3,6]
Finance	KOKO has raised venture investment and carbon finance to fund its customer acquisition and infrastructure rollout	• Collaborating with private sector and development partners to design stove financing options [5,36]. Such as the pay as go models, microcredits, rental options [37] • Provision of funding from multi-lateral organisations to conduct feasibility studies on setting up bioethanol plants (i.e., feedstock & bioethanol production) [5] • Unlock climate financing to develop the ECF ecosystem at different stages of the value chain [5] • Strengthen access to capital for SMEs through local banks to support local supply chain development [37] • Invest in energy supply and distribution infrastructure (i.e., on product transportation and local retail operations) [37] • Deploy results-based financing that can enhance biofuel enterprise economics with focus on competitiveness and sustainability of the sector [5] • Governments (through establishment of a specialised agency) can encourage clean cookstove business to access end-user finance for their products through range of proven innovative approaches, including microfinance loan schemes, payment in instalments, community savings clubs, etc. The government can do this through providing information, soft loans and loan guarantees to smaller actors seeking to set up business [6,30]
Policy support	KOKO worked with government agencies to develop industry specific	• Safety and quality issues should be addressed through government establishment of quality standards, regulation,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 August 2023 doi:10.20944/preprints202308.0884.v1

	standards and regulations which did not exist	certification and rigorous testing of stoves particularly for new designs – to ensure that they are fit, meet performance standards and safe to use [35,37,38] • Governments should expand current awareness and communication campaigns including making use of product labelling to promote ECF and highlight the risk of traditional cooking fuels [5,6,31,36,38] • NGOs can support to raise awareness of the benefits of bioethanol as a household fuel, and by providing training in stove manufacture and micro-distillery installation) [30,35,36,39] • To support market transformation of the cookstove sector, subsidies (whether carbon finance, donor or government) within cookstove businesses should generally be targeted upstream in the value chain (R&D, manufacture, distribution) rather than downstream to the end-user. Thus, targeted end-user subsidies could be used to support very low-income households to gain access to clean cookstoves [6] • Government to support demonstration projects and access to credit (i.e., carbon finance) for both the purchase of stoves and investment in micro-distilleries installation as ways of addressing barriers of adoption of bioethanol fuels and stove for cooking [6,32,35,39] • Governments should reduce the number of licenses required by cookstove manufacturers and distributors [6] or otherwise simplify registration procedures [30] • Undertake comprehensive national/local policy framework that: sets targets, establishes energy distribution, and technology strategies for urban and rural areas, and outlines plans, incentives and behaviour change and provides overall direction for the sector [13] • Zero-rating VAT on ECF is necessary to level the playing field (with other competing fuels i.e., LPG is zero rated in Kenya) [31,35]. and stimulate demand 6,5] • Short-term zero-rating of 25% import duty (i.e., on machinery for bioethanol processing and specialised supply chain equipment) for denatured bioethanol as a cooking fuel to allow establishment of local production [5,32]

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 August 2023 doi:10.20944/preprints202308.0884.v1

		• Provide tax rebates to bioethanol producers that source directly from local farmers [5] • Promote healthy competition among stove programmes, by harmonising the Bioethanol Vapour (BEV) stove import tariffs with that of LPG at 10% [5]
Stakeholders' involvement	KOKO's customer call center, distribution agent management team and commercial organisation ensures it has regular customer and other stakeholder feedback	• Attract donor support to ensure efficient sourcing from sugarcane & cassava smallholder farmers to meet projected future demands [5,35] • Build international partnerships to create opportunities for technology/knowledge transfer [5] • Private sector involvement to support promotion of bioethanol stoves by focusing on attributes that are considered most important to the cookstove user (e.g., cleanliness, attractive design, and speed of cooking) [3] • A specialised agency should be established to plan and promote clean cooking stoves, coordinate technology standards and testing and manage national and sub national data on biomass energy supply and demand [6,39] • Governments intending to introduce and strengthen bioethanol use and businesses, should strive by first establishing a policy on bioethanol [30]
Implementation of bioethanol plants	KOKO buys from both local and international bioethanol plants through its trading partners so that its supply risk is not concentrated to just one plant	• To be operated in an optimal way, bioenergy plants require a feedstock of constant quality, in sufficient quantity and at a reasonable and reliable cost [30]
Bioethanol Supply chain management and organisation	KOKO contracted global trading companies to ensure consistent and reliable bioethanol fuel deliveries	• The government should purpose to achieve a fair balance between the buying price of feedstock and the selling price of end product to allow for significant impacts on the economic, social and environmental well-being of local populations [30]
Preparation phase challenges	KOKO investors experience with a pilot project (Clean Star Mozambique) helped to mitigate market awareness challenges	• A preliminary study must include a thorough analysis of the sustainability of the whole value chain [30]

References

1. Batchelor, S. and Sieff, R. (2022). MECS and Jigsaws. Modern Energy Cooking Services programme, May. https://mecs.org.uk/blog/mecs-and-jigsaws/
2. IEA (2023). Access to clean cooking. SDG7: Data and projections. International Energy Agency, Paris. https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking
3. Farabi-Asl, H., Taghizadeh-Hesary, F., Chapman, A., Bina, S. M., & Itaoka, K. (2019). Energy Challenges for Clean Cooking in Asia, the Background, and Possible Policy Solutions. Asia Development Bank.
4. Cimini, A., & Moresi, M. (2022). Environmental impact of the main household cooking systems—A survey. Italian Journal of Food Science, 34(1): 86–113. https://doi.org/10.15586/ijfs.v34i1.2170.
5. GoK (2021). Kenya Ethanol Cooking Fuel Masterplan. Prepared by the Kenyan Government in Partnership with South North, German Government and Dalberg.
6. Lambe, F., Jürisoo, M., Wanjiru, H., and Senyagwa, J., (2015). Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action. Prepared by the Stockholm Environment Institute, Stockholm and Nairobi, for the New Climate Economy. Available at: http://newclimateeconomy.report/misc/working-papers.
7. Dalberg (2018). Scaling up clean cooking in urban Kenya with LPG & Bioethanol: A market and policy analysis. Dalberg
8. Parikh, J. (2011). Hardships and health impacts on women due to traditional cooking fuels: A case study of Himachal Pradesh, India. Energy Policy 39(12): 7587–7594.
9. Rosenthal J., Quinn A., Grieshop A.P., Pillarisetti A., and Glass R.I. (2018). Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environmental goals. Energy for Sustain Development. 42:152–159. https://doi. org/10.1016/j.esd.2017.11.003R
10. Jeswani H.K., Chilvers A., and Azapagic A. (2020). Environmental sustainability of biofuels: A review. Proc Royal Soc A. 476:20200351. https://doi.org/10.1098/rspa.2020.0351.
11. Stockholm Environment Institute (2016). Bringing clean, safe, affordable cooking energy to Kenyan households: an agenda for action. The new climate economy. Stockholm: SEI, pp.1-4.
12. Bhatia, M and Angelou, N (2015). Beyond Connections: Energy Access Redefined. ESMAP Technical Report;008/15. World Bank, Washington, DC. http://hdl.handle.net/10986/24368
13. UNIDO (2022). Unlocking the bioethanol economy: A pathway to inclusive and sustainable industrial development in developing countries. United Nations Industrial Development Organization.
14. Warwick, H. and Doig, A., (2004) Smoke: the Killer in the Kitchen, Indoor Air Pollution in Developing Countries, ITDG Publishing, London, United Kingdom.
15. UN-CTCN (2023). Ethanol Cook Stoves. Unted Nations – Climate Technology Centre & Network, UNFCC Technology Mechanisms. https://www.ctc-n.org/technologies/ethanol-cook-stoves, retrieved on 23rd May 2023.
16. Bailis, R., Pennise, D., Ezzati, M., Kammen, D., & Kituyi, E. (2004). Impacts of Greenhouse Gas and Particulate Emissions From Woodfuel Production and End-Use in Sub-Saharan Africa. Berkley University California.
17. Diaz-Chavez, R., Johnson, F., Richard, T., & Chanakya, H. (2015). Biomass resources, energy access and poverty reduction. Paris: SCOPE.
18. Pennise, D., Branta, S., Mahu Agbeve, S., Quaye, W., Mengesha, F., Tadele, W., & Wofchuck, T. (2009). Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. Energy for Sustainable Development. 13 (2): 71 - 76
19. Alexander, D., Northcross, A., Karrison, T., Morhasson-Bello, O., Wilson, N., Atalabi, O., . . . Olopade, C. (2018). Pregnancy outcomes and ethanol cook stove intervention: A randomized-controlled trial in Ibadan, Nigeria. Nigeria: Environmental International. Susan C. Anenberg, Kalpana Balakrishnan, James Jetter, Omar Masera, Sumi Mehta, Jacob Moss, and Veerabhadran Ramanathan. Cleaner Cooking Solutions to Achieve Health, Climate, and Economic Cobenefits. Environmental Science & Technology 2013 47 (9), 3944-3952. DOI: 10.1021/es304942e.
20. Zuzarte, F., 2007. Ethanol for Cooking - Feasibility of Small-scale Ethanol Supply and its Demand as a Cooking Fuel: Tanzania Case Study, KTH School of Energy and Environmental Technology, Heat and Power Technology, Stockholm, Sweden.
21. IEA (2006). World Energy Outlook, France IEA/OECD, Paris, 2006.
22. The Bioflame (2023). Four reasons to choose bioethanol fuel. Accessed on 20th May 2023 at: https://www.thebioflame.com/blog/four-reasons-to-choose-bioethanol-fuel/#:~:text=Bioethanol%20fuel%20is%3A&text=Unlike%20fuels%20like%20gas%20and,toxic%20chemicals%20or%20air%20pollutants.
23. Energypedia (2023). Ethanol Cooking Fuel in Kenya. Accessed 20th May 2023 at: https://energypedia.info/wiki/Ethanol_Cooking_Fuel_in_Kenya.

 doi:10.20944/preprints202308.0884.v1

24. Mirzabaev, A., J. Wu, J. Evans, F. García-Oliva, I.A.G. Hussein, M.H. Iqbal, J. Kimutai, T. Knowles, F. Meza, D., Nedjraoui, F. Tena, M. Türkeş, R.J. Vázquez, M. Weltz, 2019: Desertification. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. https://doi.org/10.1017/9781009157988.005
25. Putti, V.R., Tsan, M., Mehta, S., Kammila, S. (2015). The State of the Global Clean and Improved Cooking Sector. ESMAP Technical Paper; No. 007/15. World Bank, Washington, DC. http://hdl.handle.net/10986/21878
26. OECD. (2016). OECDSTAT. [online] Available at: https://stats.oecd.org/index.aspx?queryid=54757
27. Zhang, Z., Lohr, L., Escalante, C., & Wetzstein, M. (2010). Food versus fuel: What do prices tell us?. Energy policy, 38(1), 445-451.
28. Filip, Ondrej; Janda, Karel; Kristoufek, Ladislav; Zilberman, David (2017). Food versus Fuel: An Updated and Expanded Evidence, IES Working Paper, No. 26/2017, Charles University in Prague, Institute of Economic Studies (IES), Prague
29. Cartwright, A. (2007). Biofuels trade and sustainable development: An analysis of South African bioethanol.
30. UNIDO (2021). The role of bioenergy in the clean energy transition and sustainable development: Lessons from developing countries. United Nations Industrial Development Organization.
31. Thompson L. M. (2018). Cooking with Gas How children in the developing world benefit from switching to LPG. World LPG Association – WLPGA.
32. Benka -Coker, M., Tadele, W., Milano, A., Getaneh, D., Stroke, H. (2018)., A case study of the ethanol clean cook stove intervention and potential scale-up in Ethiopia. Energy for Sustainable Development, 46: 53- 64.
33. SouthSouthNorth (2021). Kenya Ethanol Cooking Fuel Masterplan. June. https://southsouthnorth.org/wp-content/uploads/2021/07/ECF-Kenya-Masterplan-cover.pdf
34. Batchelor, S.; Brown, E.; Scott, N.; Leach, M.; Clements, A.; Leary, J. Mutual Support—Modern Energy Planning Inclusive of Cooking—A Review of Research into Action in Africa and Asia since 2018. Energies 2022, 15, 5805. https://doi.org/10.3390/en15165805
35. World Bank (2011). Ethanol as a Household Fuel in Madagascar. Health Benefits, Economic Assessment, and Review of African Lessons for Scaling-up. Volume I - Summary Report.
36. Karanja, A. and Gasparatos, A. (2019). Adoption and impacts of clean bioenergy cookstoves in Kenya. Renewable and Sustainable Energy Reviews, 102: 285 – 306.
37. ESCAP. (2021). Shaping a Sustainable Energy Future in Asia and the Pacific – A greener, more resilient and inclusive energy system. Economic and Social Commission for Asia and the Pacific.
38. Mudoembi, S,. Nyambane, A., Maltitz, G, P, V., Gasparatos, A. c., Johnson, F. X., Chenene, M, L., Attanassov , B. (2018). User perceptions about the adoption and use of ethanol fuel and cookstoves in Maputo, Mozambique. Energy for Sustainable Development, 44: 97 – 108.
39. USAID and Winrock International (2017). Clean and efficient cooking technologies and fuels. https://winrock.org/wp-content/uploads/2017/09/WinrockCookstoveCombined.pdf