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

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Abstract: Expansion in access to clean cooking in Sub-Saharan Africa remains well below the UN's Sustainable Development Goal objectives. In particular, clean and modern forms of cooking have struggled to attract commercial funding at scale. 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 its launch 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 the charcoal normally used for cooking; a leading cause of African deforestation. This development is so recent that it has not been widely 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. The main aim of this study is to identify how KOKO Networks has managed to overcome the traditional barriers to scalability, achieving impacts with bioethanol for accelerating energy transitions for cooking. The results show that bioethanol for cooking supports 13 out of 17 SDGs and has significant positive impacts on health, the environment, and the wider economy. The affordability of bioethanol has been made possible because of KOKO Investments in high-tech electronic fuel dispensing machines and through the use of climate financing. KOKO relies both on local and imported fuel to offer reliability and security of supply, as well as to grow commercial bioethanol demand to support the growth of the local bioethanol industry. Bioethanol for cooking also suffers from unfavorable tax regimes. This is because historically, in many countries, ethanol has been imported for use in the beverage industry. In addition, an appropriate commercial supply chain and delivery model which boosts the scalability of business and offers customer convenience is essential. For these conditions to take place, an enabling policy environment is key.

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

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1. Introduction

Despite research and policy initiatives targeting the challenges of clean cooking access and the significance of new strategies for attaining SDG 7, the government funding available for clean cooking objectives in many countries is still a small fraction of the 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 this 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 concentrate on cooking solutions and have received support from a variety of results-based finance and technical assistance programs such as the Clean Cooking Alliance Venture Program. However, only a few of them have a customer base exceeding a few thousand households. Furthermore, many of these clean cooking companies sell solutions using 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, it has never been commercialized. Its recent large-scale adoption has motivated reviews of the evidence regarding the potential positive impact of bioethanol and potential implications for research and policy. To date, the reviews that have been undertaken are limited and are largely focused on either bioenergy/biofuels or clean cooking. Even among the few studies available, the analyses on bioethanol for cooking are not comprehensive, with some studies separately focusing on impacts, while others focus on barriers to scalability. Furthermore, there are no studies that have been done to jointly demonstrate the barriers to scalability of bioethanol for cooking and its potential benefits using a case study, in particular, the case of KOKO Networks. Lastly, this paper utilizes the MECS TToC framework for the first time to understand both the barriers to scalability and the impacts of bioethanol for cooking.

Focusing on the new development of a largescale bioethanol utility, the study's main objective is to provide a review of the impacts and barriers to scalability of bioethanol for accelerating energy transitions for cooking. The analysis is informed by several methods including the use of secondary data, case studies, lessons learned, and the MECS TToC framework.

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 the expected current and future barriers to scalability; (iii) examine in detail the KOKO bioethanol utility growth and the challenges it has faced and overcome in light of the MECS TToC model; and (iv) provide the implications of this analysis for further scaling of modern energy clean cooking.

This article is organized as follows: Section 1 provides an introduction to the study and Section 2 provides a literature review of bioethanol for cooking, including the associated impacts and contributions to SDGs. Section 3 discusses the methodology that applies to understanding the barriers to scalability of bioethanol fuels and stove technologies for cooking. Section 4 presents the results and largely discusses the implications of large-scale bioethanol cooking in East Africa. The paper ends with conclusions and recommendations for scaling-up bioethanol for cooking.

2. Bioethanol for Cooking Literature Review

Bioethanol is among the few fuels used for cooking that have the potential for positive health [3], climate and environmental benefits [4], gender equality [5], increased employment opportunity, earnings, time, and fuel saving impacts [6], 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. It has received the least amount of attention, despite its performance attributes 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 the approach. The absence of a rigorous analysis of the benefits, as well as of the historical barriers to scalability, currently limit 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 available empirical evidence and the outcomes of a 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 have focused on transitions 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 the health risks associated with exposure to indoor air pollution from household fuel combustion. According to the World Bank's Multi-Tier Framework for cooking [12], in 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 organized based on three impact categories: health, climate and environment, and economic and opportunity costs. It also provides a summary of how bioethanol supports the achievement of a range of SDGs.

2.1. Health Impacts

This section explores the evidence on the health benefits of using bioethanol for cooking. The discussion highlights the illnesses/diseases that may emanate from using unclean fuels and stoves and the possible health improvements of switching to 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 ischemic heart disease (IHD), stroke, lung cancer, chronic obstructive pulmonary disease (COPD) in adults, and acute lower respiratory infection (ALRI) in children [3,8,13], with greater risks among poor populations [14]. Additionally, because of women's role in cooking and caring for children in Sub-Saharan Africa, they are highly exposed to the pollutants/particles produced from incomplete combustion, leading to respiratory and eye disorders and a high incidence of death, approximated at 1.6 million/year [15].

There is a growing consensus that use of improved stoves with the same solid biomass fuel does not significantly reduce the negative health effects associated with open-fire cooking. For example, ref. [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 obtain funding, since bioethanol has been commercialized at scale, empirical evidence for the health benefits of bioethanol-fueled cookstoves specifically is still relatively scarce. However, refs. [16,17] both show that cooking with bioethanol is a cleaner and healthier alternative, and ref. [15] includes it as one of the options for improved health conditions delivered from cooking with a clean smokeless fuel.

In Ethiopia, ref. [18] investigated the impact of using a bioethanol stove on indoor pollutants instead of inefficient cooking with wood. In their study, wood was 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. Ref. [18] and others showed 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, demonstrating the implications of bioethanol for cooking and pregnancy. Recent evidence from Nigeria shows that switching to bioethanol-fueled stoves has the potential to provide needed protection for women and their developing fetuses [19].

Ref. [7] reported on their own literature review of the emissions caused by different cooking fuels (firewood, charcoal, kerosene, LPG, and bioethanol) and concluded that bioethanol and LPG offer the greatest and most broadly comparable health benefits.

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

2.2. Environmental Impacts

The environmental impacts of cooking discussed in this section include 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 summarized.

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 emitted by plants during photosynthesis [13]. Ref. [9] shows that the use of other cleaner fuels (i.e., LPG and biogas) offers lower greenhouse gas (GHG) emission reductions. Bioethanol emissions with sugarcane bagasse as a feedstock can meet the European Union Renewable Energy Directive of a 60% reduction in GHG emissions relative to petrol and other agricultural and forest sources [10]. In terms of air pollution, beyond being associated with a reduction in indoor air pollution, bioethanol is also associated with improved outdoor air quality [13]. In terms of its impacts on other media, bioethanol is considered to be biodegradable; therefore, its use reduces the 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 ref. [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 the tree cover has a chance to regenerate. There are significant emission reductions associated with 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 are evident. Figure 1 presents an overview of the health and climate impacts of a wide range of fuel and stove combinations; however, these are averages, and their actual performance varies widely. However, bioethanol is included in region 4, with the least health and climate implications, which is a cluster of modern renewable fuels including bioethanol and biogas [3].

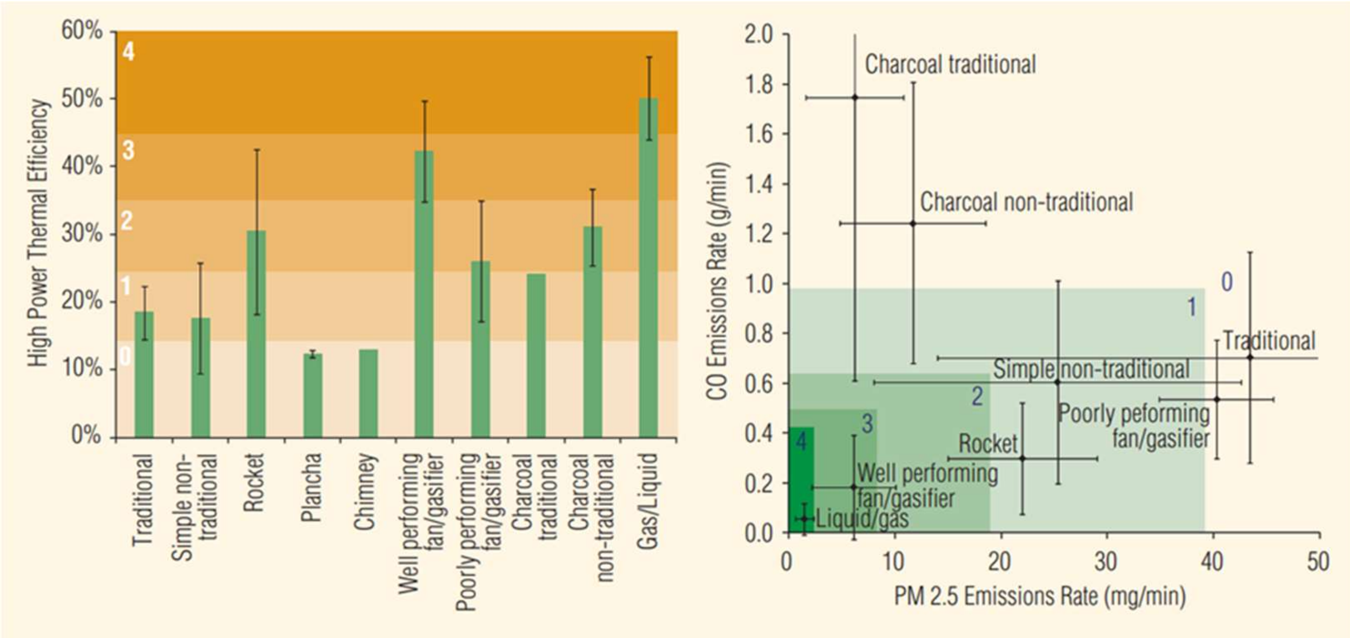

Figure 1. Health impacts and climate impacts of cooking technologies. Source: [25].

2.3. Economic and Opportunity Cost Impacts

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

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

There has been 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 due to household air pollution, there are very significant local benefits to a fuel switch which 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 its social and environmental impact, and as it can attract 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, restricting production to the needs of local markets and requiring registration of producers for fuel tax rebates [29]. Rather than threatening food security, Cartwright in his study concludes that there is a 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 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 level, national level, 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, the 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 the National Level (Kenya) Biomass	At the Household Level (Kenya) Bioethanol	At the National Level (Kenya) Bioethanol	Sub-Saharan Africa Solid Fuels [a]
Environmental	• Deforestation and forest degradation: Kenya loses 10.3 million m^3 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 tons of CO_2 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 ton 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 kg 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: 728 k disability-adjusted life years (DALYs) and 16.6 k deaths annually [e] • 8–10% of early deaths in Kenya [b,c] • Lower respiratory tract disease is the third largest contributor to deaths in Kenya [e] • Pneumonia is a major cause of death in children under the age of five, largely due to indoor air pollution [e]	• ~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 for a liquid than pressurized gas [e]	• Disability-adjusted life years (DALYs) averted: Up to 507,000 DALYs [c] • Deaths averted: ~3700 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 problems in billion USD: low ($0.1), mid ($0.8) and high ($1.5) [f]

Table 1. *Cont.*

Impact Category	At the National Level (Kenya) Biomass	At the Household Level (Kenya) Bioethanol	At the National Level (Kenya) Bioethanol	Sub-Saharan Africa Solid Fuels [a]
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 min 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 for producing 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, 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.

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

SDGs	Bioethanol for Cooking Contributions
SDG 1: No Poverty	The time saved by 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 bioethanol fuel dispensing machines. Potential to support farmer incomes from locally sourced fuel
SDG 2: No Hunger	Investing in the 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 using bioethanol for cooking improves health conditions through a reduction in exposure to 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 the time spent on cooking and collecting fuel for the household [13,30]

Table 2. *Cont.*

SDGs	Bioethanol for Cooking Contributions
SDG 5: Gender Equality	The time saved as a result of using 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 impacts 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 lower-income populations [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 the bioethanol industry will require innovations in bioethanol production, introducing innovative farming practices and agricultural zoning research. A clear concept for the 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 the 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]

2.5. Understanding Barriers to Scalability of Bioethanol Fuels and Stove Technologies for Cooking

Historically, increasing the 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 a relatively high cost due to unfavorable tax and tariff treatments 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. This section reviews previous studies of these scaling barriers. According to [3,7], the success of clean cooking programs in developing countries is possible by prioritizing accelerating awareness creation. According to [6], in their study that focuses on bringing clean, safe, and affordable cooking energy to households across Africa, governments in Sub-Saharan Africa could encourage the uptake of clean cooking stoves and their components by removing taxes and duties to exempt technologies that are imported and by reducing the number of licenses required by cookstove manufacturers and distributors. A study by [7] also found that increasing uptake is possible through affordable prices for clean cooking stoves and fuels. Bioethanol cooking fuel is less expensive because of climate-financed discounts, which support its clean, sustainable production and sale in affordable bundles. Bioethanol cooking fuel is thus a viable and scalable modern cooking fuel with the potential to be sold at prices affordable to most urban Kenyans currently relying on kerosene and charcoal [6]. The study notes that if the government of Kenya made (denatured technical) bioethanol zero-rated for VAT and eliminated tariffs, it would be among the cheapest cooking fuel options in Kenya and could displace charcoal and kerosene.

Ref. [3] examined the background, challenges, and possible policy solutions for clean cooking in Asia. The study has several findings and recommendations on how to strengthen consumer preference and demand. The study first establishes that clean cooking programs are mainly successful in cities; households in rural areas face difficulties in receiving the incentives for the programs. Furthermore, the study observed that a considerable number of clean cooking programs in Asia are subsidies for fossil fuels, as they target the promotion of LPG for cooking. The study asserts that enhancing the awareness of women about clean cooking technologies and improved cookstoves is fundamental, and that a comprehensive set of actions for enhancing awareness is necessary to guarantee the success of clean cooking programs in developing countries. The study also suggests that conducting impactful research on modelling of consumer choices for cooking fuels in countries, as well as developing the right business model for scaling-up the clean cooking market, is helpful for successful design and implementation of clean cooking policies and programs.

A hindrance to scale-up of bioethanol programs has been the lack of access to business and startup finance to access cookstoves and fuel distribution technology [6]. Access to financial support for clean cooking business and low-income households' stoves has been investigated by several authors [5,6,30,33,34]. These studies provide recommendations for access to finance for businesses and low-income households. The underlying message is that access to financial support should be addressed based on the use of the finances; generally, either for capital investment and end-user finance for final products produced, or as end-user subsidies to support low-income households for access to clean cookstoves. Scaling up of bioethanol for cooking also requires specific technology for the production and collection of sufficient raw materials, their purchase at a fair price, and their 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]. Refs. [3,6,35] separately examined stove and fuel technology as challenges for clean cooking in Asia and Africa. They recommended that local innovation be aligned with customer feedback and matched with finance and policy access support that is easily accessible by international partners.

Several studies [3,5,6,30,35,36] have analyzed the effects of stakeholder's participation on bioethanol cooking scaleup from the government, donor community, private sector, internal partners, and specialized agency. These studies conclude that actors in the bioethanol sector have unique roles they play, covering the provision of financing [5,35], creation of technology/knowledge transfers [5], promotion of stoves [3,6,36], development of policy [30], and development of a specialized agency focused on the promotion of the bioethanol industry [6,36].

In addition to stakeholders' involvement, finance, and development of technology, ref. [30] argues that to enable energy transition and sustainable development in developing countries, the implementation of bioethanol plants, management, and the organization of the supply chain requires feedstock supplies to be specific, affordable, adequate, and of reliable quality and quantity. According to [30], a preliminary study of the bioethanol sector value chain is critical; it enables the identification of challenges and possible mitigation measures, thus ensuring sustainability of the value chain.

Addressing challenges in both the supply chain and initial/preparatory phases is crucial for scaling up bioethanol for cooking. Similar findings were also reported by ref. [32]. The study reports that ethanol as a household fuel demonstrates some potential for scale-up and commercialization, but it may require simultaneous stabilization of the ethanol supply, growth of a city-wide distribution infrastructure, and affordably priced stoves and fuel.

Policies, standards, and the regulatory environment [6] can each pose implementation challenges for companies. 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 subsidized fossil fuels. Analyses of plans, policies, standards, and regulations for supporting the growth of the bioethanol and clean cooking subsectors has been done by several authors. Refs. [34,35,37] conclude that new stove designs should be subjected to safety and quality standards as well as product labelling to guarantee their performance and standards. In addition, with regards to the bioethanol businesses for cooking value chain, refs. [6,30] suggest that the government should reduce the number of licenses and simplify the business registration procedures, respectively.

Given the importance of creating awareness and communication on the benefits of cooking with bioethanol and the risks thereof, a range of empirical evidence show that both governments and non-governmental organizations have been responsible for effectively undertaking information and educational campaigns [5,6,31,33,37]; providing various training on bioethanol for cooking, including stove manufacture and micro-distillery installation) [30,33,35,36]; and supporting the demonstration of projects and access to credit [6,32,35,38].

Governments are accountable for ensuring that there is an enabling environment and policy that promotes healthy competition in the energy cooking subsector. Evidence shows that for some countries, funding of LPG for cooking has been favored and supported by subsidies and lower/no taxation over time [5,6,31,35]. To support bioethanol for cooking, governments working with non-governmental organizations should introduce the use of subsidies or facilitate climate finance to help with affordability, targeting both the businesses in the upstream level of the value chain and lower-income end users to finance the purchase of stoves [6]. This will offer a level playing field where bioethanol enjoys a zero-rated VAT and import duty of machinery required for bioethanol processing and distribution, enabling and boosting domestic production [5,6,31,35]. Furthermore, ref. [5] concludes that the provision of tax rebates by governments is critical for strengthening the local production of bioethanol.

KOKO in Kenya has managed to overcome most of these barriers through a long process of addressing each one over a series of years, giving 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. A further detailed analysis is provided in Appendix A.

3. Materials and Methods

3.1. MECS TToC

This study deployed the modern energy cooking services transition theory of change (MECS TToC) framework to analyze the expected current and future barriers to scalability and examine in detail the KOKO bioethanol utility growth and the challenges it has faced and overcome. The MECS TToC has three dimensions. The consumer demand dimension of the MECS TToC framework focuses on the demand side barriers and uptake factors (from marketing strategies to market segmentation) to the scalability of bioethanol fuel and stove technology. The supply chain dimension of the MECS TToC framework targets obstacles and enables the scalability of bioethanol fuel and stove technology. The identified supply chain and delivery models' obstacles and enabling factors aim to highlight the supply side challenges/drivers, stakeholders providing cooking products/services, and scalable business models. The enabling environment dimension of the MECS TToC framework prioritizes the challenges and drivers to bioethanol for cooking ecosystems, from mapped stakeholders, explored interventions, and promoted projects or programs. A diagrammatic of MECS TToC is presented in Figure 2.

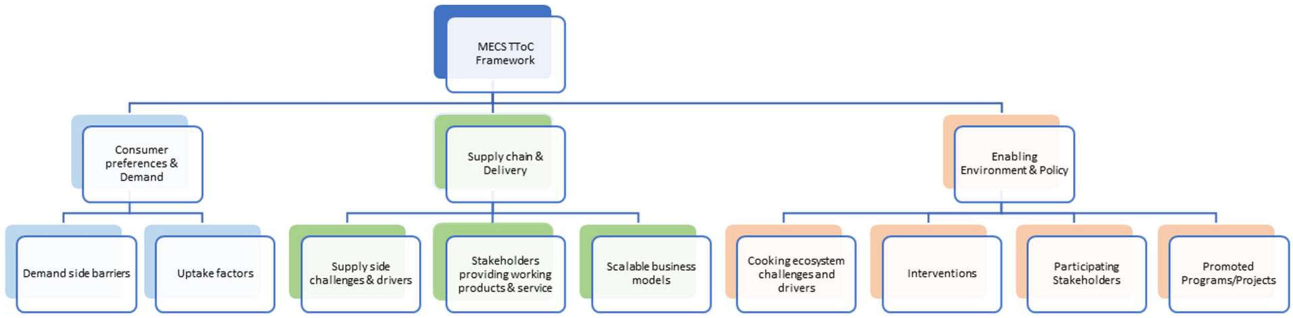

Figure 2. MECS TToC.

Before applying the MECS TToC framework, the study utilized secondary data, case studies, and lessons learned as methods of collecting data, which are discussed below.

3.2. Secondary Data

The use of secondary data from both scientific (mainly Scopus) and grey literature from various sources were obtained to analyze the impact and investigate the growth and barriers to scalability of bioethanol for cooking. Table 3 summarizes the studies that were used in the review.

Table 3. Summary of previous studies reviewed.

Impacts/Benefits of Bioethanol				Growth and Barriers to Scalability	
Impact Category	**Previous Studies**	**Contributions to SDGs**	**Previous Studies**	**MECS TToC**	**Previous Studies**
Environment	[3,5–7,9,10,13,15,22–25]	**SDGs 1–5**	[13,29,30]	**Consumer preferences and demand**	[3,6,7]
Health	[3,5–9,13–21,25]	**SDGs 6–10**	[13,30]	**Supply chain and delivery model**	[3,5,6,30,32–36]
Economic/ Opportunity costs	[5–7,13,26–29]	**SDGs 11–15**	[13,30]	**Enabling environment and policy**	[5,6,30–37]

3.3. Case Study and Lessons Learned

The study also used KOKO as a case study to offer a systematic and in-depth learning experience and to demonstrate the influence of scaling up bioethanol for cooking. In addition, the study uses lessons learned method to demonstrate KOKO's real experiences and feedback to the wider clean cooking sector.

KOKO Networks is an international venture-backed technology company. The company's unique suite of technologies connects suppliers, retailers, and customers, enabling the delivery of a range of consumer and business solutions. Important to this review, KOKO offers a consumer cooking solution involving both a stove and an ongoing supply of liquid bioethanol cooking fuel (aimed at replacing charcoal), which delivers significant cost savings and quality of life improvements in the multi-billion-dollar market for urban cooking fuel. The company has over 1800 staff in East Africa and India. It is currently operating in eight major cities in Kenya, including Nairobi, Kisumu and Nakuru.

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 its preceding commercial pilot venture, CleanStar Mozambique.

Bioethanol had been identified by the investors in CleanStar Ventures as a promising potential solution for tackling 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 fuel supplies. 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 supply security for consumers, which is essential for 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 exist worldwide, even in remote and rural areas. This is unlike the compressed gas fuel infrastructure needed for LPG, which is costly to build. Therefore, bioethanol for cooking addresses the first and third TToc dimensions, where the development of the bioethanol industry leads to job and income generation, provides security of the fuel supply, and allows for easy transportation and storage of fuel. 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 it 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 centralized bottling method of distribution of bioethanol was not financially viable, and in the view of the management, it was 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 barrier to further scaling.

4.2. Development of New Cooking Fuel Distribution Technology

CleanStar Ventures then set out to develop a 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, from 2014 to 2019, developing new hardware and software technology in Nairobi and Kampala preparing the launch of a new bioethanol fuel utility model which overcame the structural challenges of the centralized bottling mode of bioethanol cooking fuel distribution. Inspired by milk-dispensing automated teller machines (ATMs) used in India, they saw dispensing machines based in small neighborhood 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 also provided this service using two additional unique pieces of hardware: a smart filling system at a petrol station and a smart sensor on top of a micro-tanker fuel truck which refills the dispensing machines. At each stage, the fuel temperature and surrounding vapor is regularly checked by the machines for any leaks, spills, or tampering, reporting back remote data via a cloud-based monitoring system. The system is run as a fuel utility, with most dispensing machines refueled every day by a fleet of micro-tankers which are dispatched from a network operations center (NOC) which uses software and a 24 h monitoring team to minimize 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 for establishing safety for consumers needed to be drafted and agreed upon with the Kenya Bureau of Standards before it launched in Kenya, its first consumer market. These standards and regulatory protocols included calibration of the dispensing machines, bioethanol cooking stoves, the requirement to color and denature the bioethanol so that it could not be accidentally ingested, and the testing of each bioethanol batch.

Another important piece needed for the supply chain puzzle was long-term access to storage infrastructure for transporting and storing bioethanol to enable dispensing it to consumers. 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 pieces of the enabling environment puzzle were aligned, notably that regulation of the sector fit into government policy. In addition to the existing government 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. The plan was completed in June 2021 and involved broad consultation both inside and outside of government [38].

4.3. Innovations in Climate Finance

The company was designed to be financed through the sale of carbon credits to 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 United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (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 in 2021, KOKO began marketing its credits to 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 and charcoal. The higher that 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 in-house manufacturing facility, and a network operations center. They were 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 navigating the challenges of lockdowns, social distancing, and staff illness, sudden international and local shortages of bioethanol, which was needed for hand sanitizer, caused initial supply issues. These issues did not settle until the beginning of 2021, after which the growth of this 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. Their customers are spread across eight cities and towns in Kenya. The network of dispensing machines grew in tandem with the customer base, reaching 2000 machines in early 2023. In 2022, KOKO signed an investment agreement with the Government of Rwanda to launch a nationwide bioethanol cooking fuel utility, planning 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 decreases meal preparation time, and the fuel dispensing machines are strategically designed to be a 5 min 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 that enable the policy environment.

5. Discussion

5.1. Implications for Policy: The Potential for a Fuel Switch to Bioethanol

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 cooking stoves (ICS). Similar results were observed by ref. [3]. Zero rating of both VAT [31,35] and import duties [5,32] and the provision of targeted subsidies for end-user business at the upstream value chain and among lower income households is critical for enhancing the adoption of bioethanol for cooking. Through significant investment in technology and funding from climate finance, KOKO has been successful in bringing bioethanol for cooking to scale. Support from climate finance makes the solution affordable, even for non-urban customers, over time.

The demonstrable benefits for forest protection, health, and contributions to economic gains in African countries, alongside support for 13 of the SDGs, suggests that bioethanol cooking fuel should be explicitly considered for energy access, forest protection, and climate finance policy, alongside other modern energy cooking options, notably electricity and biogas. with regard to forest protection, according to ref. [15], bioethanol fuel is considered to be carbon neutral and can allow for regeneration of tree cover, reducing pressure on forest resources [30], reducing agriculture deterioration, and enhancing food security [5,13]. Bioethanol for cooking replaces fossils fuels and traditional biomass; thus, it can support climate policy through the reduction of GHG emissions from households, which are estimated to contribute between 30–40% of Kenya's GHG emissions [5,7]. With the ability to be distributed in smaller volumes, bioethanol fuel can be easily accessed at affordable prices [7], contributing to SDG 7. In addition, bioethanol promotes health policies, as it is observed to offer the greatest and most broadly comparable health benefits compared to fossil fuels and traditional biomass [7].

Large scale bioethanol use can accelerate affordability, minimize 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 regulations, local large-scale sustainable bioethanol production and its associated supply chains will be developed, stimulating jobs and local economic development. Ref. [6] established that companies are likely to face implementation challenges when there is a lack of enabling policies, standards, and a regulatory environment. Thus, with the need for proper planning, refs. [6,36] suggest the development of a specialized agency focused on the promotion of the bioethanol industry. The characteristics of the fuel itself are important for the benefits achieved, but so too is the design of the customer-facing fueling infrastructure, as also found by [39].

Given that climate finance so far is explicitly available for the bioethanol cooking model due to its impact on forest protection, the model is suitable for countries with high rates of deforestation or those which have sources of funding other than climate finance, such as a government or donor subsidy program. According to refs. [6,32,35,36], such financing should prioritize setting demonstration projects, purchasing stoves, capital investments such as machinery. An enabling policy environment for a bioethanol fuel utility also requires minimizing taxation—excising duty, value added tax (VAT), and import duty—to enable affordability for target households that are currently reliant on the cheapest fuels available. Refs. [5,31,32,35] note that the provision of targeted subsidies for end-user businesses at the upstream value chain and among lower-income households is critical for enhancing the adoption of bioethanol for cooking.

5.2. Lessons from the Transition Theory of Change

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

While the success of KOKO as a business and the success of its cooking fuel utility have many origins, careful attention to the 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 businesses and also provides customer convenience. Finally, careful attention to the enabling environment, including deforestation, climate policy drivers, and health and safety, was crucial. Finding technical solutions, both for the fuel type and delivery infrastructure, that ticked all these boxes has enabled rapid scaling (as presented in Appendix A, Table A1).

5.3. Practical Implication of the Study

Bioethanol fuel offers a similar cooking experience to gas, burns cleanly, and cooks faster than traditional fuels. Bioethanol for cooking supports 13 out of the 17 SDGs, and as this study shows, it has significant positive impacts on health, the environment, and the wider economy. Due to the importance of bioethanol for cooking, increasing the demand for cooking with bioethanol should be encouraged. By making bioethanol for cooking affordable, KOKO has been able to expand their consumer base, scaling this form of clean cooking considerably. The affordability of bioethanol has been made possible largely through KOKO investment in high-tech electronic fuel dispensing machines which lower the cost of distribution, and because of the use of climate financing, which is related to the impact of reduced demand for charcoal on deforestation rates. This paper's analysis of the drivers and barriers of this scaling offers insights that other clean cooking developers can learn form, with practical benefits in terms of the future uptake of clean cooking and economic development.

This paper also offers practical insights for policymakers and donors. Growing commercial bioethanol demand is crucial for supporting the growth of the local bioethanol industry. Currently, the KOKO supply model relies on both local and imported fuel to offer reliability and supply security. A climate financing model should be prioritized in countries with serious deforestation issues, and donor and government subsidy programs can also be targeted to promote affordability and capital investments in bioethanol for cooking. Unfavorable tax regimes hamper the growth of bioethanol for cooking, which are a legacy in many countries due to their history of ethanol being imported for use in the beverage industry. KOKO's cooking fuel has been chemically denatured so that it can only be used for cooking.

5.4. Limitations of the Research

This study uses secondary data to present the results of the impacts of bioethanol for cooking. The presented estimates of the impact vary from one empirical study to another due to the different methods deployed to estimate the impacts. Thus, there is a need for future research to estimate the impacts of bioethanol for cooking to inform policy formulation and industry development.

Using KOKO as a case study is not representative of the entire industry for commercialization and scale-up; thus, future research should consider completing secondary findings based on other stakeholders' perceptions and insights through primary data collection.

6. Conclusions

Using KOKO, a large bioethanol utility as a case study, this article offers a review of the benefits of using bioethanol for cooking, in addition to presenting the growth and barriers to scaling up bioethanol. This study made use of secondary data, case studies, and lessons learned, alongside the MECS TToC framework to address its aims. The success of KOKO in reaching mass market adoption can be explained systematically through the application of the MECS TToC framework. The framework has three dimensions which are critical to explaining the growth and barriers to scalability of bioethanol for cooking.

KOKO was able to address consumer preferences and demand creation barriers through the provision of a gas-like fuel with a rapid, modern, and convenient cooking experience that is affordable, complemented with a two-burner stove that decreases meal preparation time. The fuel dispensing machines are strategically designed to be a 5 min walk from the customers' homes. The presence of a robust and commercially viable supply chain that provides avenues for job and income generation was made possible through local production and the import of supplies that also guarantee the reliability and security of the fuel supply. The distribution of bioethanol fuel to consumers is made possible through years of research and development in fuel distribution technology and long-term agreements between KOKO and Vivo energy to utilize Vivo use storage tanks under conveniently located petrol stations spread across 23 countries. KOKO was also able to address the consumer preferences, demand, supply chain, and delivery model barriers through use of climate financing, making investments in stoves, fuel distribution technology, and continuous research and development. Lastly, by enabling the environment, a specific bioethanol cooking master plan and bioenergy strategy have been developed by stakeholders to regulate the sector. In addition, KOKO Networks worked with the Kenya Bureau of Standards to develop hardware and fuel standards for consumer safety.

This study presents several impacts of bioethanol for cooking, prioritizing health, the environment, and to the wider economy. It also summarizes the contribution of bioethanol to SDGs. Bioethanol for cooking is reported to support 13 out 17 SDGs. KOKO was able to successfully scale and commercialize bioethanol cooking. The industry is reliant on continued supportive changes for enabling the environment. In some places, legacy policies developed for beverage ethanol are barriers to growth for the bioethanol for the cooking industry, which should be overcome as knowledge grows about developments in the sector.

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

Abbreviations

ALRI	Acute Lower Respiratory Infection (ALRI)
ATM	Automated Teller Machine
CDM	Clean Development Mechanism
CO	Carbon Monoxide
COPD	Chronic Obtrusive Pulmonary Disease
ECF	Bioethanol Cooking Fuel
GHG	Green House Gases
HAP	Household Air Pollution
ICS	Improved Cooking Stoves
IHD	Ischaemic Heart Disease
KOKO	KOKO Networks
LPG	Liquid Petroleum Gas
MECS	Modern Energy Cooking Services
PM	Particulate Matter
SADC	Southern African Development Community
SDG	Sustainable Development Goals
TToC	Transition Theory of Change (MECS TToC)
UNFCC	United Nations Framework Convention on Climate Change.
VAT	Value Added Tax
WHO	World Health Organization

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	Examples of Theoretical Recommendations for Bioethanol Cooking Scale Up from the Existing Literature
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]
Finance	KOKO has raised venture investment and climate finance to fund its customer acquisition and infrastructure rollout	• Collaboration with private sector and development partners to design stove financing options [5,33], such as pay as you go models, microcredits, and rental options [34] • 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 [34] • Invest in energy supply and distribution infrastructure (i.e., on product transportation and local retail operations) [34] • 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 specialized 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. [6,30]

Table A1. *Cont.*

Barriers/Success/ Scale-Up Factors	KOKO Experience	Examples of Theoretical Recommendations for Bioethanol Cooking Scale Up from the Existing Literature
Policy support	KOKO worked with government agencies to develop industry specific standards and regulations which did not exist	• Safety and quality issues should be addressed through government establishment of quality standards, regulation, certification and rigorous testing of stoves particularly for new designs—to ensure that they are fit, meet performance standards and safe to use [34,35,37] • 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 [5,6,31,33,37] • NGOs can support awareness of the benefits of bioethanol as a household fuel) [30,33,35,36] • Targeted end-user subsidies could be used to support very low-income households to gain access to clean cookstoves [6] • Governments can support demonstration projects and access to credit (i.e., climate finance) for both the purchase of stoves and investment in production as ways of addressing barriers of adoption of bioethanol fuels and stove for cooking [6,32,35,36] • 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] • New, supportive tax policy for 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 [5,6]
Stakeholders' involvement	KOKO's customer call center, distribution agent management team and commercial organisation ensures it has regular customer and other stakeholder feedback	• 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] • Governments intending to introduce and strengthen bioethanol use and businesses, should establish a policy for 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 develop policy to help ensure local feedstock is commercially competitive to allow for significant positive 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	• Pilot studies should include a thorough analysis of the of the whole value chain [30]

References

1. Batchelor, S.; Sieff, R. MECS and Jigsaws. Modern Energy Cooking Services Programme. May 2022. Available online: https://mecs.org.uk/blog/mecs-and-jigsaws/ (accessed on 16 March 2023).
2. IEA. Access to Clean Cooking. SDG7: Data and Projections. International Energy Agency, Paris. 2023. Available online: https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking (accessed on 16 March 2023).
3. Farabi-Asl, H.; Taghizadeh-Hesary, F.; Chapman, A.; Bina, S.M.; Itaoka, K. *Energy Challenges for Clean Cooking in Asia, the Background, and Possible Policy Solutions*; Asia Development Bank: Hong Kong, China, 2019.
4. Cimini, A.; Moresi, M. Environmental impact of the main household cooking systems—A survey. *Ital. J. Food Sci.* **2022**, *34*, 86–113. [CrossRef]

5. GoK. Kenya Ethanol Cooking Fuel Masterplan. Prepared by the Kenyan Government in Partnership with South North, German Government and Dalberg. 2021. Available online: https://southsouthnorth.org/wp-content/uploads/2021/07/ECF-Kenya-Masterplan-cover.pdf (accessed on 16 March 2023).
6. Lambe, F.; Jürisoo, M.; Wanjiru, H.; Senyagwa, J. 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 online: http://newclimateeconomy.report/misc/working-papers (accessed on 16 March 2023).
7. Dalberg. *Scaling up Clean Cooking in Urban Kenya with LPG & Bioethanol: A Market and Policy Analysis*; Dalberg: New York, NY, USA, 2018.
8. Parikh, J. Hardships and health impacts on women due to traditional cooking fuels: A case study of Himachal Pradesh, India. *Energy Policy* **2011**, *39*, 7587–7594. [CrossRef]
9. Rosenthal, J.; Quinn, A.; Grieshop, A.P.; Pillarisetti, A.; Glass, R.I. Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environmental goals. *Energy Sustain. Dev.* **2018**, *42*, 152–159. [CrossRef] [PubMed]
10. Jeswani, H.K.; Chilvers, A.; Azapagic, A. Environmental sustainability of biofuels: A review. *Proc. R. Soc. A* **2020**, *476*, 20200351. [CrossRef]
11. Stockholm Environment Institute. Bringing clean, safe, affordable cooking energy to Kenyan households: An agenda for action. In *The New Climate Economy*; SEI: Stockholm, Sweden, 2016; pp. 1–4.
12. Bhatia, M.; Angelou, N. *Beyond Connections: Energy Access Redefined*; ESMAP Technical Report; 008/15; World Bank: Washington, DC, USA, 2015; Available online: http://hdl.handle.net/10986/24368 (accessed on 21 March 2023).
13. UNIDO. *Unlocking the Bioethanol Economy: A Pathway to Inclusive and Sustainable Industrial Development in Developing Countries*; United Nations Industrial Development Organization: Vienna, Austria, 2022.
14. Warwick, H.; Doig, A. *Smoke: The Killer in the Kitchen, Indoor Air Pollution in Developing Countries*; ITDG Publishing: London, UK, 2004.
15. UN-CTCN. Ethanol Cook Stoves. Unted Nations—Climate Technology Centre & Network, UNFCC Technology Mechanisms. 2023. Available online: https://www.ctc-n.org/technologies/ethanol-cook-stoves (accessed on 23 May 2023).
16. Bailis, R.; Pennise, D.; Ezzati, M.; Kammen, D.; Kituyi, E. *Impacts of Greenhouse Gas and Particulate Emissions from Woodfuel Production and End-Use in Sub-Saharan Africa*; Berkley University California: Berkeley, CA, USA, 2004.
17. Diaz-Chavez, R.; Johnson, F.; Richard, T.; Chanakya, H. *Biomass Resources, Energy Access and Poverty Reduction*; SCOPE: Paris, France, 2015.
18. Pennise, D.; Branta, S.; Mahu Agbeve, S.; Quaye, W.; Mengesha, F.; Tadele, W.; Wofchuck, T. Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. *Energy Sustain. Dev.* **2009**, *13*, 71–76. [CrossRef]
19. Alexander, D.; Northcross, A.; Karrison, T.; Morhasson-Bello, O.; Wilson, N.; Atalabi, O.; Dutta, A.; Adu, D.; Ibigbami, T.; Olamijulo, J.; et al. *Pregnancy Outcomes and Ethanol Cook Stove Intervention: A Randomized-Controlled Trial in Ibadan, Nigeria*; Environmental International: Nigeria, West Africa, 2018.
20. Zuzarte, F. *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, 2007.
21. IEA. *World Energy Outlook*; IEA; OECD: Paris, France, 2006.
22. The Bioflame. Four Reasons to Choose Bioethanol Fuel. 2023. Available online: 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 (accessed on 20 May 2023).
23. Energypedia. Ethanol Cooking Fuel in Kenya. 2023. Available online: https://energypedia.info/wiki/Ethanol_Cooking_Fuel_in_Kenya (accessed on 20 May 2023).
24. Mirzabaev, A.; Wu, J.; Evans, J.; Garcia-Oliva, F.; Hussein, I.A.G.; Iqbal, M.H.; Kimutai, J.; Knowles, T.; Meza, F.; Nedjroaoui, D.; et al. 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*; Shukla, P.R., Skeg, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, S., et al., Eds.; Cambridge University Press: Cambridge, UK, 2019. [CrossRef]
25. Putti, V.R.; Tsan, M.; Mehta, S.; Kammila, S. *The State of the Global Clean and Improved Cooking Sector*; ESMAP Technical Paper; No. 007/15; World Bank: Washington, DC, USA, 2015. Available online: http://hdl.handle.net/10986/21878 (accessed on 5 July 2023).
26. OECD. OECDSTAT. 2016. Available online: https://stats.oecd.org/index.aspx?queryid=54757 (accessed on 16 March 2023).
27. Zhang, Z.; Lohr, L.; Escalante, C.; Wetzstein, M. Food versus fuel: What do prices tell us? *Energy Policy* **2010**, *38*, 445–451. [CrossRef]
28. Filip, O.; Janda, K.; Kristoufek, L.; Zilberman, D. *Food Versus Fuel: An Updated and Expanded Evidence*; IES Working Paper, No. 26/2017; Charles University in Prague, Institute of Economic Studies (IES): Prague, Czech Republic, 2017.
29. Cartwright, A. *Biofuels Trade and Sustainable Development: An Analysis of South African Bioethanol*; International Institute for Sustainable Development: Winnipeg, MB, Canada, 2007. Available online: https://www.iied.org/sites/default/files/pdfs/migrate/G02285.pdf. (accessed on 16 March 2023).
30. UNIDO. *The Role of Bioenergy in the Clean Energy Transition and Sustainable Development: Lessons from Developing Countries*; United Nations Industrial Development Organization: Vienna, Austria, 2021.

31. Thompson, L.M. *Cooking with Gas How Children in the Developing World Benefit from Switching to LPG*; World LPG Association—WLPGA: Neuilly-sur-Seine, France, 2018.
32. Benka-Coker, M.; Tadele, W.; Milano, A.; Getaneh, D.; Stroke, H. A case study of the ethanol clean cook stove intervention and potential scale-up in Ethiopia. *Energy Sustain. Dev.* **2018**, *46*, 53–64. [CrossRef] [PubMed]
33. Karanja, A.; Gasparatos, A. Adoption and impacts of clean bioenergy cookstoves in Kenya. *Renew. Sustain. Energy Rev.* **2019**, *102*, 285–306. [CrossRef]
34. ESCAP. *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: Bangkok, Thailand, 2021.
35. World Bank. Ethanol as a Household Fuel in Madagascar. In *Health Benefits, Economic Assessment, and Review of African Lessons for Scaling-Up*; Volume I—Summary Report; World Bank: Washington, DC, USA, 2011.
36. USAID and Winrock International. Clean and Efficient Cooking Technologies and Fuels. 2017. Available online: https://winrock.org/wp-content/uploads/2017/09/WinrockCookstoveCombined.pdf (accessed on 16 March 2023).
37. Mudombi, S.; Nyambane, A.; von Maltitz, G.P.; Gasparatos, A.; Johnson, F.X.; Chenene, M.L.; Attanassov, B. User perceptions about the adoption and use of ethanol fuel and cookstoves in Maputo, Mozambique. *Energy Sustain. Dev.* **2018**, *44*, 97–108. [CrossRef]
38. SouthSouthNorth. Kenya Ethanol Cooking Fuel Masterplan. Available online: https://southsouthnorth.org/wp-content/uploads/2021/07/ECF-Kenya-Masterplan-cover.pdf (accessed on 30 June 2021).
39. 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. [CrossRef]