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Innovation in distributed energy services for sustainable development: case studies from sub-Saharan Africa

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Abstract

In this work, we explore how locally led innovations can advance sustainable energy access in low-income regions of Africa. Given the emphasis of the Sustainable Development Goals on the importance of affordable, reliable, and sustainable energy, we critically assess how local innovations can address the unique challenges of regions characterized by informality and low purchasing power and where existing grid-based electricity supply is weak. Through case studies, we highlight successful initiatives in expanding energy services access, including product bundling, pay-as-you-go financial models, leveraging existing supply chains, and securing strong funding support. Our findings underscore the importance of local ownership, contextual knowledge, and the adaptation of innovations to specific socio-economic and cultural conditions. By comparing the case studies, we identify common strategies that can contribute to the effectiveness of local innovations in improving energy access and sustainability that can inform efforts to replicate and scale up such initiatives. We conclude by identifying common elements contributing to the success of these cases and their significance, focusing on those crucial for achieving speed, scale, and impact.

1. Introduction

The United Nations 2030 Agenda, with its seventeen Sustainable Development Goals (SDGs), has helped galvanize global attention and effort to achieve a universal set of social, economic, and environmental objectives. However, progress has been uneven across the set of goals and regions (Sagar *et al* 2023, UN 2023). Even before COVID-19, disparities in progress were evident (Zhao *et al* 2022). The pandemic and international conflicts have further hindered efforts, making it highly likely that many goals will be missed, especially in already lagging regions (UN, Independent Group of Scientists appointed by teh Secretary-General 2023, IEA, IRENA, UNSD, World Bank, WHO 2024).

Sub-Saharan Africa (SSA), home to many low and lower-middle-income countries (LMICs), is notably behind in achieving the SDGs, despite its vast natural resources and needs. About 40% of Africans live in extreme poverty (AUC, UNECA, AfDB, UNDP-RBA 2022). The number of undernourished people in SSA increased from 172 to 264 million between 2010 and 2020 (FAO 2021), and those deprived of clean cooking access rose from under 600 million to well over 900 million between 2000 and 2022 (IEA, IRENA, UNSD, World Bank, WHO 2024). This situation is partly attributable to insufficient infrastructure and energy services, which are essential to improve living standards and productivity (Falchetta *et al* 2020).

Slow progress on the SDGs in SSA and other LMICs is also due to unequal access to innovations and limited capacity for innovation (Arnold 2018, Sagar *et al* 2023). Other challenges include informality and low purchasing power, low capital intensity and skill levels, weakly networked basic infrastructures, high transaction costs and weak institutions, and low credit access and high cost of capital (Ameli *et al* 2021). These factors deter private investment (AfDB 2022). Additionally, international

public financial flows for clean energy in developing countries in 2022 were only half of their peak in 2016 (IEA, IRENA, UNSD, World Bank, WHO 2024). Most existing finance has gone to large, centralized power generation. Despite this, expansion of central grid infrastructures remains protracted and inadequate. This has spurred new innovations in distributed modular solutions to expand energy services access (Gebreslassie *et al* 2023). Climate offsets are emerging as a potential new source of finance but current emissions accounting methods, as well as monitoring, verification and reporting are underdeveloped and incongruent (Gill-Wiehl, Kammen, and Haya 2024). Bridging finance gaps is crucial for infrastructure investment and anti-poverty efforts in support of the SDGs, given limited national public budgets and large fiscal deficits (Sennoga and Balma 2022, Abanikanda *et al* 2023).

Scholarship on innovations in distributed modular solutions that aim to reduce poverty and expand energy services access in LMICs remains scant (Byrne *et al* 2014, Kammen and Jacobs 2014, Ockwell and Byrne 2016). To address this gap in the literature, we examine case studies of inclusive and local innovations in SSA for expanding access to energy services in low-income regions and communities. These cases, selected largely for ease of data availability, span innovations across sectors. They include solar irrigation in East Africa (Aptech Africa and SunCulture), solar-powered cold storage in Nigeria (Koolboks), and efforts to improve clean cooking access in Kenya and Tanzania (KOKO Networks and Circle Gas).

Our objective is to identify common themes and insights from these case studies to understand factors that have enabled the emergence and growth of these innovations that target low-income communities with their varied localized energy needs and circumstances, and what has contributed to their achievements. We find common elements such as product or service bundling, pay-as-you-go (PAYGO) financial schemes with digital payment, leveraging existing supply chains and local networks, and strong funding support across these cases.

In the following section, we first present a short description of methods. In section three, we briefly introduce each case. We carry out a cross-case comparison to draw insights from across the cases in section four. In the final section, we conclude with a brief discussion of our findings and key overarching implications.

2. Methods

In this work, we aimed to explore from across disparate cases whether there are commonalities in how innovations to address SDG7 are manifesting in SSA and specifically, how the challenges of serving low-income communities and customers to alleviate energy poverty are being addressed. Innovation can have a crucial role in alleviating poverty in all its forms. Early studies on innovation for poverty alleviation generally either viewed the poor as a vast untapped market (Prahalad 2012) or as proponents of grassroots innovations in resource constrained environments, often drawing on traditional knowledge and cheap, locally available raw materials (Smith *et al* 2014). More recently, there has been a shift in the discourse that emphasizes the importance of broadening the scope of innovation to encompass products, processes, business models and supply chains. This discourse also considers a broader set of actors including corporates, the state, and most importantly, local actors (consumers and businesses) that can together deliver welfare enhancing products and services to deprived sections of society (Foster and Heeks 2013, Chataway *et al* 2014). Such an approach resonates with the energy technology innovation system (ETIS) framework, which considers the systemic nature of innovation, and that has been applied to many empirical case studies of energy technologies in the past (Gallagher *et al* 2012, Grubler and Wilson 2014).

Our case studies are from varied geographical contexts and sectors and address different energy deprivations and end uses. While all of them are contemporary, they vary in terms of the timespan of their respective operations. For all the cases, we applied a qualitative inductive approach, with a view to being able to synthesize and compare across the cases, to ultimately derive common insights and lessons (Bartlett and Vavrus 2016).

Our exploratory empirical case studies, and their analysis, build on the expertise of the co-authors and their practical knowledge and direct experience with their respective cases. We relied on peer reviewed literature, commercial, government and institutional documents, newspaper and magazine articles, and webpages. We used relevant keywords, such as the company name, key technologies, and actors to identify relevant sources. For some of the cases, semi-structured conversations with key actors were also undertaken.

To synthesize from across the case studies, we considered innovations from across three different concurrent dimensions including product and service innovation, process and business model innovation, and supply chain innovation. Inclusive innovation in these three distinct spheres have also been highlighted in the literature as being particularly relevant (Kalkanci *et al* Toktay 2019). Following this, we then derived descriptive insights synthesizing from across

the cases on each of these dimensions to identify common cross-sectoral innovation approaches.

3. Background and key characteristics of the case studies

The slow progress with achieving the SDGs in SSA and other LMICs, calls for creativity and innovation. In recent years, the concept of inclusive innovation, i.e. 'development and implementation of new ideas which aspire to create opportunities that enhance social and economic well-being for disenfranchised members of society' has gained traction (George *et al* Prabhu 2012). Inclusive innovation harnesses local ingenuity i.e. originates from and operates in civil society and thus, can be more localized, context specific and socially determined. In the case studies described briefly below, we first provide a brief background to the issue, and then a short description of the cases. In section four we carry out a cross case assessment that zooms in on specific common innovative elements and how these manifested across the cases.

3.1. Solar irrigation in the farm sector in East Africa (Aptech Africa and SunCulture)

More than half of the population in SSA depends on agriculture for labor and income (Goedde *et al* 2019) and about 80% of agricultural production in the region is from smallholder farmers (AGRA 2014, Connolly-Boutin and Smit 2016). Rain-fed agriculture is practiced on over 90% of cropland, under erratic rainfall patterns (Abrams 2018). Along with agricultural mechanization (Gumbe 2020) and land fertilization (Thomas 2020), irrigation has significant potential (Burney *et al* 2010, IRENA 2021, FAO, IFAD 2021, Falchetta 2021, Amuakwa-Mensah and Surry 2022) to increase land productivity (Hillocks 2014, Rosa *et al* 2018, Falchetta *et al* 2023), food production and farmer revenues while saving land resources (Davis *et al* 2016, Jayne *et al* 2019).

To pump water on-demand and use pressurized irrigation systems requires electricity. However, the limited extent of the central power grid infrastructure in rural SSA means that irrigated farms mostly use diesel powered gensets to pump water from aquifers and basins and distribute it onto fields. Aptech Africa, a Uganda-based company with branches active in different East, Central and West African regions, is bundling already commercially mature small-scale irrigation infrastructure (pumps and irrigation system, including sprinklers and fittings) and cost-competitive renewable electricity supply systems (PV plus battery modules), and using so-called 'pay-n-pump' and 'pay-as-you-grow' business models (figure 1), thus supporting the upfront cost burden for individual farmers (Xie, Ringler, and Mondal 2021). Aptech Africa is locally led (its CEOs and the majority of employees are from SSA) and strongly relies on innovation, digitalization and ICTs, as key means to enable financial inclusion (Figuères 2013). For instance, it allows for making digital payments for the pumps, as the kits are GSM PAYGO & Internet of Things (IoT) enabled, but it can also remotely lock the system in case of non-payment.

After just over a decade of activity, Aptech Africa has been rather successful. It has installed over 1000 solar and water pumping projects across Africa and in 2021 it generated more than $6 million in revenues while witnessing a strong growth in employee headcount. Other Eastern African companies, such as SunCulture (which recently earned a revenue of $30 million and is managing to raise a significant amount of private funding), are also expanding their businesses in the region, despite being founded by non-local entrepreneurs. Whilst headquartered in Nairobi, SunCulture has 13 local branches scattered across the main agricultural districts of Kenya, and it is also seeking to expand business in additional African countries.

Financing solutions adopted by companies like Aptech Africa and SunCulture are allowing farmers to pay small monthly fixed fees, while only charging farmers through a pre-paid service with a fee per liter that includes lifetime maintenance and irrigation training in proportion to the extent of utilization of the appliance. In additional, these systems are often coupled by companies which leverage their strong local networks to promote marketing campaigns, regional sales and support centers, industry advocacy, and local capacity building trainings (in cooperation with public authorities) to increase awareness and knowledge of their existence and utilization.

Overall, local companies based on 'pay-n-pump' and 'pay-as-you-grow' models are showing promising potential to transform the solar irrigation market in Africa. Rather than engaging in R&D for new technological products, these companies are focusing on bundling existing technologies (e.g. small-scale submersible pumps, solar PV panels, Li-ion batteries, and GSM antennas and digital payment protocols) and developing innovative business models that leverage local public-private networks to overcome entry barriers to the technology, as well as capacity development challenges.

3.2. Solar-powered cold storage in Nigeria (Koolboks)

Access to cold storage in SSA also remains a huge challenge. An estimated 30%–40% of total food production in the region is lost to waste (FAO, IFAD, UNICEF, WFP and WHO 2023). Cold chain technologies are especially critical for small and medium-sized businesses handling perishable food products and health clinics distributing vaccines. The poor electricity grid infrastructure availability and reliability, and high tariffs are a major constraint to developing effective cold storage solutions in the region.

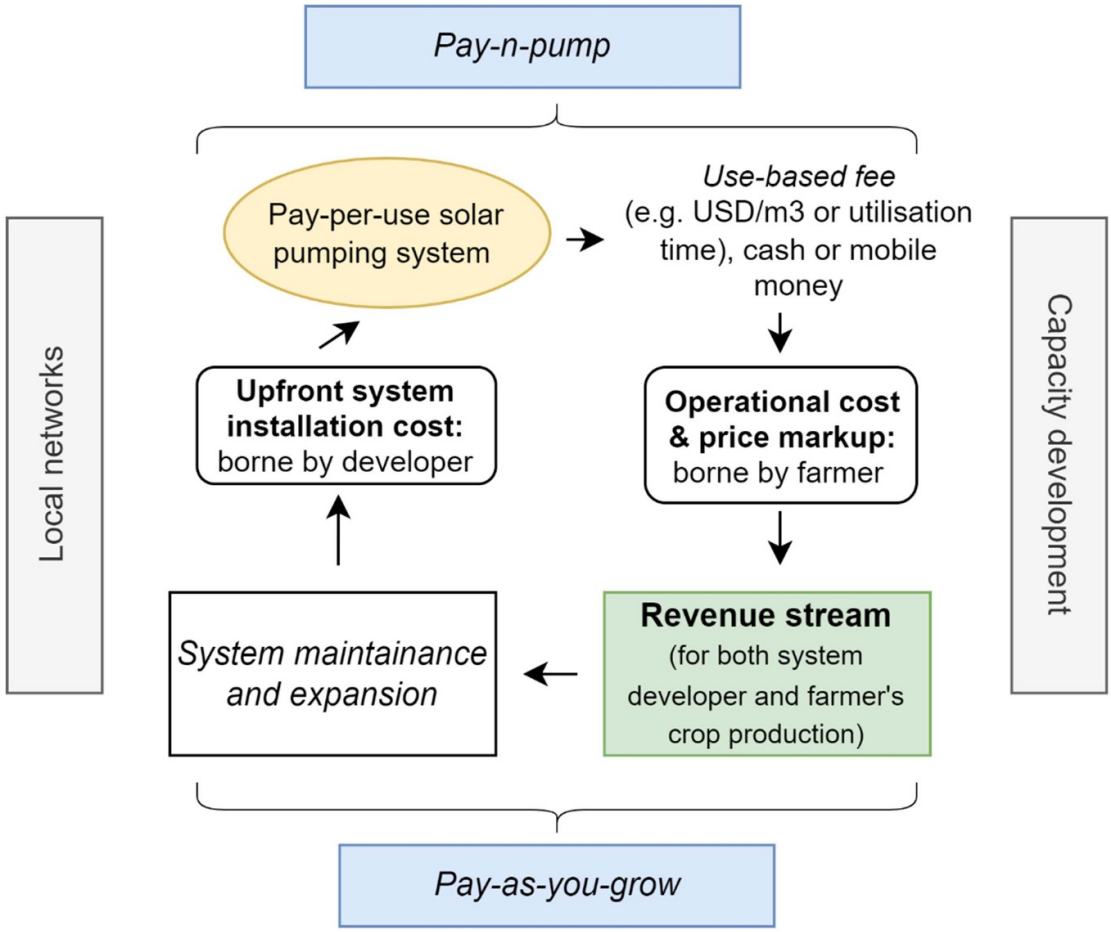

Figure 1. Framework of integrated 'pay-as-you-grow' and 'pay-n-pump' business models innovation for solar irrigation systems diffusion. Authors' elaboration.

Koolboks, a French-Nigerian start-up, has developed and integrated a set of innovations to address these barriers, offering a solar-powered pay-as-you-go (PAYG) refrigerator with increased autarky through ice-batteries in combination with lithium-ion (Li-ion) battery storage. Their signature product began as a solution for outdoor campers in the EU but quickly pivoted entirely to focus on the sub-Saharan African market and its specific challenges and opportunities. They address barriers faced by sub-Saharan African customers in several ways: (i) by offering affordable GSM-based PAYG and 'cooling-as-a-service' models, (ii) by increasing autarky (and reducing cost) through the novel ice-battery concept, and (iii) by bundling other key energy service needs with their product—namely device charging via USB and LED lighting (Efficiency for Access Coalition 2021).

The design for the Koolboks ice-battery drew on in-house experience in the pharmaceutical sector in Nigeria, specifically the transportation of crucial vaccines in remote regions of the country. Prior to their innovation, this distinct but ultimately quite similar use for 'off-grid' refrigeration had not been considered to address consumer market needs, with refrigerators primarily designed for mains power connection and generator backup among the urban and wealthy. Realizing this innovation quickly relied on the ability to access international supply chains. The refrigerator itself is sourced in China and retrofitted with the ice-battery, PAYGO controller, and Li-ion battery trolley in Nigeria. Following rapid growth and favorable Nigerian government policies with respect to taxes and manufacturing regulations for solar-PV oriented firms, it is expected that the entire manufacturing chain will be transferred to Nigeria to vertically integrate and reduce import duties (Space in Africa 2020)

Along with a favorable regulatory environment and availability of international supply chains reducing up-front capital requirements for the start-up, the rapid growth of mobile money providers across the continent has been instrumental to their success in meeting market needs. Recent interviews suggest

that up to 90% of customers are paying in instalments using either the PAYGO or 'cooling-as-a-service' model (Maritz 2022). Digitalization and telecommunications expansion across the continent enabling mobile phone services and mobile money provision are thus crucial elements enabling Koolboks' innovation. Koolboks collaborates with local service providers to deliver and maintain its Cooling-as-a-Service (CaaS) equipment (Nain and Bhasin 2022).

Initial seed financing for this effort was obtained through the Efficiency for Access Research and Development Fund (UK) and the GSM Association (UK). Subsequent growth and operational finance have been secured through a mix of Nigerian and international private equity investors, including All-On Nigeria (a domestic energy access focused impact investor) and the Nigerian Sterling Bank (a fast mover in the domestic energy access space). In terms of business model innovation, the 'cooling-as-a-service' model was developed with support from the Basel Agency for Sustainable Energy's incubator programme (Efficiency for Access Coalition 2021). Koolboks were recently awarded further research and development funding through a project led by Inclusive Energy Ltd (UK) as part of Innovate UK's Energy Catalyst Programme. The project (2023–2025) is centered on the deployment of Inclusive Energy's Cloud Solar remote monitoring technology and will allow Koolboks to expand their 'cooling-as-a-service' model through data driven modeling—enabling preventative maintenance and system optimization. Koolboks has already entered markets in 18 countries, of which 13 are in sub-Saharan Africa.

3.3. Clean cooking fuel and stove access in East Africa (KOKO Networks and Circle Gas)

Halfway into the 2030 Agenda, progress on SDG 7.1's universal energy access target has been mixed. In 2022, 0.9 billion people in SSA lacked access to clean cooking, with seven countries having less than 10% access. Improvements in access rates have not kept pace with population growth in the region, doubling the access deficit since 1990 (IEA, IRENA, UNSD, World Bank, WHO 2024). Increased access has co-benefits across multiple SDGs (ESMAP 2022, Annelise *et al* 2024, Mperejekumana *et al* 2024) and has led to recent political momentum to prioritize clean cooking in policy and financing (G7 Italia 2024 2024). While rural areas face challenges to improving access due to freely and locally available biomass, urban regions of SSA still rely heavily on charcoal. Several commercial initiatives in East Africa particularly target urban markets. Here, we focus on KOKO Networks of Kenya and KopaGas (now Circle Gas) of Tanzania.

KOKO Networks, an international technology company, founded in 2014, entered the Kenyan clean liquid fuel market in December 2019 by partnering with Vivo Energy, which owns and operates Shell-branded fuel distribution infrastructure, to pioneer a decentralized approach to last-mile distribution of bioethanol as a cooking fuel to households in Nairobi (Serafeim *et al* 2024). It has built technology that leverages Vivo Energy's infrastructure for bioethanol distribution. KOKO Networks selected bioethanol as the cornerstone of its business model in Kenya based on local fuel supply, a proof-of-concept that demonstrated high consumer demand for ethanol as a cooking fuel, and several years of research and development aimed at lowering its cost to end use consumers, including by optimizing the fuel distribution chain (The Leafy Agenda 2021, MECS, Energy 4 Impact 2022, Koko Fuel Solution 2023).

The offer made by KOKO Networks is for a two-burner clean cookstove with an integrated fuel canister. A large network of cloud connected e-commerce vending machines, like ATMs, hosted inside local shops, called 'KOKO Points', serve as customer access points from where consumers purchase bioethanol in branded KOKO fuel canisters on a PAYGO basis. This sales model is designed to align with Kenyan customers' typical spending patterns of frequent, small transactions. KOKO Networks also offers customers an interest-free layaway scheme that enables them to purchase a cookstove via a small deposit and incremental instalments with no minimum payment or time limit for payments. This instrument seeks to further address affordability challenges while removing the need to offer consumer credit (MECS, Energy 4 Impact 2022, Koko Fuel Solution 2023).

Despite the disruption caused by COVID-19, KOKO Networks has grown rapidly. It now operates in eight major Kenyan cities and employs more than 1800 staff, having grown its employee base from 500 in 2019. Scale is attributed to customer perceptions of bioethanol as a convenient and affordable cooking fuel that decreases meal preparation time, and its availability near households via KOKO Points (Osiolo *et al* 2023).

KopaGas of Tanzania was also founded in 2014, with a business model grounded in smart logistics and metering to provide last-mile LPG distribution to urban communities in Dar-es-Salaam (Ndunguru 2021, MECS, Energy 4 Impact 2022). The company fits a smart valve and meter system atop an LPG cylinder Customers are not charged upfront for their cooking system but rather credit funds to a digital wallet and are charged for their LPG usage on a PAYGO basis. The smart valve and meter technology remotely monitors usage and regulates fuel supply to align with customers' credit balance. This allows consumers to track and manage their LPG consumption and to purchase fuel in quantities that fit their budgets using mobile payments, which are registered on the smart

meter using IoT technology (Ndunguru 2021, MECS, Energy 4 Impact 2022).

By late 2018, KopaGas had distributed 2000 smart meters in Tanzania with plans for significant scale up. However, it was constrained by access to finance and by August 2019 had expanded its customer base only modestly to 3500 households (Ndunguru 2021, MECS, Energy 4 Impact 2022). In January 2020, London-based Circle Gas Limited acquired the company's KopaTech technology for USD 25 million, by which time KopaGas had become the largest PAYGO LPG company in Tanzania (MECS, Energy 4 Impact 2022, Circlegas 2023). Circle Gas' acquisition of KopaGas enabled it to expand the operations of its Kenyan subsidiary, M-Gas, which launched its Kenyan PAYGO business in January 2020 and is considered the only LPG-based cooking company to have reached significant scale in SSA (Perros *et al* 2024). M-Gas maintains an operating agreement with Safaricom, Kenya's largest telecommunications company and a strategic investor in Circle Gas, with mobile money payments in Kenya processed using Safaricom's M-PESA payment service (Gillespie 2020, MECS, Energy 4 Impact 2022).

Customers cite low up-front costs, fuel affordability and accessibility, and household savings relative to charcoal expenditure as benefits of Circle Gas' clean cooking solution. Business growth has occurred despite the perceived high cost of LPG metering technology, high-risk nature of the PAYGO LPG business model, a PAYGO premium over the average end-user price of full-cylinder LPG, and fundraising challenges that reflect investor ambivalence towards LPG as a fossil fuel (Ndunguru 2021, Perros *et al* 2024).

3.4. Key characteristics and achievements across the considered cases

In table 1, we highlight some of the key achievements across the cases, given available information. Strong funding support from government donors and/or private investors underpin the achievements in each case. A comprehensive impact evaluation does not exist for any of the case studies and goes beyond the scope of this work. Here, we highlight key potential benefits, without any quantification of these.

4. Cross case comparison of key innovations

In this section, we examine some of the key innovative measures adopted in a cross-case comparison to study what was implemented in these very different contexts. We first consider the different forms of innovations that were undertaken (table 2). In this table, we compare the cases to assess whether there were elements of innovation common across them and whether there were aspects that were specifically aligned to expanding access for low-income communities and customers.

Some clear commonalities are visible across the cases. First, each of the cases features some element of product or service bundling. Second, the business or financial model in each comprises of PAYGO with digital payment options that allow for incremental and flexible payments. Third, there is an element of piggy backing on existing supply chain infrastructure and local networks across all cases. To align operations to serve varied needs of marginalized and low-income communities, a further two aspects characterize the cases. First, making the services affordable by adopting the PAYGO with digital payment appears to be the preferred way to lower entry barriers for customers by eliminating minimum payment or deposit requirements and allowing for incremental and flexible payments that can be synced with uncertain discretionary cash flows of low-income populations. It also has the advantage of reducing costs associated with customer payment default by enabling automatic discontinuance of service. Second, making the services accessible by being in the vicinity of, and responsive to the needs of, customers. All cases illustrate the potential to provide accessible services to end-users. This is achieved by working with local distributors and service agents and using local networks.

5. Discussion and conclusions

In this work, we examine case studies of innovations for improving access to energy services in SSA, with a focus on low-income populations and regions. Through comparing these cases, we identify common elements in the types of innovation undertaken and strategies that have facilitated targeting and reaching low-income communities. Our analysis underscores the significance of inclusive innovation in alleviating poverty and achieving the SDGs in LMICs. We find that a system of interconnected innovations involving product and service processes, business models, and supply chains is crucial to ensure access and affordability for low-income populations. These cases demonstrate that combining supply-side innovations, such as product or service bundling or leveraging existing supply chains and local networks, with demand-side innovations, such as adjusting business models to ensure access and affordability for low-income customers, is essential. Furthermore, the use of more modular and granular technological solutions, as illustrated by these case studies, can be advantageous for increasing accessibility, simplifying management, and reducing investment requirements, as also highlighted in literature (Wilson *et al* 2020).

We have identified common elements contributing to the achievements in these cases and their importance to scaling up such efforts in the future. Here, we briefly discuss these commonalities, emphasizing the ones we consider most important for achieving speed, scale, and impact, and thus might be the most critical to inform further efforts by public

Table 1. Comparison of case studies achievements.

	Aptech Africa and SunCulture		Koolboks	KOKO Networks and Circle Gas	
Years of operation	Since 2012	Since 2013	Since 2018	Since 2014	KopaGas since 2014, acquired by Circle Gas in 2020
Countries of operation	Founded in Uganda. Also. working in Central African Republic, Liberia, South Sudan, Sierra Leone, Rwanda	Founded in Kenya (13 local branches). Also working in Côte d'Ivoire, Ethiopia, Senegal, Uganda, Zambia	Founded in France and then Nigeria. Also working in Ghana, Senegal, Ivory Coast, Sierra Leone, Liberia, Kenya, Uganda	Founded in Kenya. Also working in Rwanda	Founded in Tanzania. Also working in Kenya
Funding secured	Development finance (e.g. USAID/Power Africa; Électricité de France) and international bond issuance	Raised US$27.5 million in 2024 of which $12 million is to enhance its solar irrigation solution[c]	Secured $2.5 million in 2022[e]; Results based financing from BGFA in 2023 for expanding operations in Uganda[f]; European donor seed finance, + domestic and international equity finance	Venture capital and private equity (including Microsoft Climate Innovation Fund equity investment in 2022), impact investors, and commercial lenders.[i] Raised USD 100 million in carbon finance through 2023[j]	Donor grants for technology development (GSMA, DFID, MIT D-Lab); social and impact investment (Acumen, Saisan, Hooge Raedt Social Venture, D-Prize); Circle Gas USD 25 million acquisition in 2020; Safaricom and Marubeni Corporation corporate investment[m]

(Continued.)

Table 1. (Continued.)

	Aptech Africa and SunCulture		Koolboks	KOKO Networks and Circle Gas	
Growth in devices sold/ customers	75 000 people and over 1000 solar and water pumping projects across Africa till 2022[a]	47 000 units till 2024[d];	At least 3000 freezers sold by 2021[g]	Customer growth: 20 000 (early 2020); 100 000 (March 2021) 500 000 (June 2022); 950 000 (June 2023)[k]	250 000 customer households as of 2024[m]
Potential benefits (across different SDGs)	SDG1—Higher earnings; SDG2—Better crop yields; SDG6—Water saving; SDG7—Improved access to efficient, affordable and reliable renewable energy services; SDG8—Creation of local jobs; SDG10—Reduced inequalities; SDG12—Better quality of life; SDG13—Avoided CO2 emissions [b]		SDG2—Better food preservation; SDG5—Women's empowerment; SDG7—Improved access to efficient, affordable and reliable renewable energy services; SDG8—Creation of local jobs; SDG12—Reduced waste generation; SDG13—Avoided CO2 emissions[h]	SDG3—Improved health from reduced household air pollution; SDG5—Gender equality from shortened cooking and fuel collection times; SDG7—Improved access to efficient, affordable and reliable cooking fuels (renewable in the case of KOKO networks; cleaner in the case of Circle Gas); SDG8—Creation of local jobs; SDG13—Avoided GHG emissions[l]	

Notes:

[a] Source: https://aptechafrica.com/.

[b] Source: (ARE, UNIDO, and ITPO 2021, USAID 2021).

[c] Source: https://disruptafrica.com/2024/04/12/kenyas-sunculture-raises-27-5m-in-oversubscribed-series-b-funding-round/.

[d] Source: https://techpoint.africa/2024/04/11/sunculture-raises-funding-expand-solar-irrigation/.

[e] Source: https://techpoint.africa/2022/08/18/koolboks-secures-seed-expand-nigeria/.

[f] Source: https://beyondthegrid.africa/news/solar-powered-off-grid-energy-solutions-in-uganda-supporting-development-in-rural-communities/.

[g] Source: www.koolboksnigeria.com/kool-impact.

[h] Source: https://acumen.org/case-studies/koolboks/.

[i] Source: www.bloomberg.com/news/articles/2024-01-23/rmb-boosts-african-carbon-business-with-offset-backed-loan; Koko Fuel Solution (2023); MECS, Energy 4 Impact (2022).

[j] Source: www.ft.com/content/5ab93324-685d-43c8-b30d-b5332b1a378d.

[k] Source: (ESMAP 2022, MECS, Energy 4 Impact 2022, Circlegas 2023).

[l] Source: (Osiolo *et al* 2023).

[m] Source: (Circlegas 2023).

Table 2. Comparison of case studies across different innovation dimensions.

	Aptech Africa and SunCulture	Koolboks	KOKO Networks and Circle Gas
Technical innovation	Bundling of small-scale submersible pumps, solar kit (and optional battery storage) + remote monitoring/intervention	Ice-battery increasing product autarky + energy service bundling + remote monitoring	KOKO Networks: stove + integrated fuel canister + automated fuel purchase points + remote monitoring Circle Gas: fuel canister + smart meter + remote monitoring
Financial/ business model Innovation	Risk and private discount rate reduction through product bundling Combination of 'pay-n-pump' and 'pay-as-you-grow' + digital payments	'Cooling-as-a-service' model and PAYGO + digital payments for lease-to-own option	KOKO Networks: PAYGO + digital payments + interest-free layaway scheme Circle Gas: PAYGO + digital payments
Supply chain Innovation	Service provision-oriented technological bundling	Initial component sourcing for rapid prototyping and market entry through Chinese suppliers/transitioning to local manufacturing during growth phase.	KOKO Networks: wholly owned ethanol cooker manufacturing facilities in India + ethanol distribution partnership with Vivo Energy + local shops for fuel ATMs + fuel delivery vehicles designed for local road conditions. Circle Gas: smart metering technology for enhanced monitoring of LPG consumption and more efficient last mile delivery + leveraging local LPG distributors

and private players to scale up access to sustainable energy services in the region.

5.1. The significance of demand data and remote monitoring

An important insight from the case studies relates to the importance of demand data to support decision-making by private service providers, customers, and investors. Generating such data is challenging in the environments in which these businesses operate. The cases highlight the value of incremental data improvement through remote monitoring and the role of digital technologies. Such systems have direct operational benefits such as improving inventory planning and supply chain management, as well as iterative design benefits including product design and sizing. Such systems can also allow for diagnostic troubleshooting, an important value addition for providing customer support and with remote access control providing the secondary service of repayment enforcement. At the same time, these systems can also be leveraged to give customers a greater sense of agency through an improved ability to monitor and manage their own energy use, thus overcoming a critical barrier to sustained adoption by building confidence and trust. Across the cases, we also observe that demand-side data can improve businesses' understanding of consumer profiles and preferences and allow them to refine their business models accordingly. For example, both KOKO Networks and KopaGas launched their PAYGO clean cooking offers in markets where consumers were familiar with the idea of instalment payments, thereby benefiting from a high level of consumer awareness of this payment method (ESMAP 2022).

5.2. Leveraging local value chains and content

The cases show that it was advantageous to leverage local value chains and content even while local manufacturing capacity is built. By integrating locally sourced labor, resources, and expertise, costs were lowered, solutions became more relevant and acceptable, while also boosting local economies. Engaging local businesses and stakeholders also helped foster community support, which is crucial for the long-term success and expansion of such initiatives. For instance, KOKO networks partnership with local owner-operated mini-marts for their kiosks, helped ensure proximity, create awareness among customers and did away with the need for building their own retail space. These cases demonstrate that by developing local capabilities and value chains, a self-reinforcing cycle of innovation and development is created, which can ultimately contribute to broader economic and social objectives. This approach is not only important to scaling up such initiatives but can also ensure that the benefits are equitably distributed within the communities they aim to serve.

5.3. Application of smart technologies and modular designs

The cases also saw benefits from the application of smart technologies, such as digital payments, and modular design elements. The modular designs, which involved bundling existing technologies into adaptable, scalable solutions, provided several advantages. The flexibility offered by such systems is especially useful in LMICs, where diversity in economic conditions and energy needs is immense, and tailoring solutions to local contexts to ensure they are relevant and effective is essential. The use of smart technologies also facilitated better data collection and management, providing valuable insights into usage patterns, payment behaviors, and system performance. The use of digital payments and modular designs can also enable such energy access initiatives to reach a larger number of low-income households and communities, helping achieve scale. Specifically, technology bundling with financing can serve as an effective business model to make services financially available to low-income customers. This is exemplified, for instance, by SunCulture's partnership with a micro-finance institution to offer a 'pay as you grow' model, bundling its solar-powered drip irrigation system with tailored financing that includes an upfront payment and a multi-year loan repayment plan.

5.4. Role of public policy and macro conditions

Public policy played a pivotal role in each of the cases, either as an enabler or impediment. For instance, in KOKO Networks' case, the company's operating environment was enabled by the Kenyan government's bioenergy strategy and bioethanol cooking master plan, which recognizes the positive social, environmental, and economic impacts of a local bioethanol cooking industry. Yet, a more favorable taxation environment for ethanol is needed to improve its affordability for households that rely on the cheapest available fuels (Osiolo *et al* 2023). By contrast, financial and logistical bottlenecks resulted in supply chain disruptions, and weakened macroeconomic conditions, including currency volatility and exchange rate risk, high fiscal deficits, and capital cost increases impacted businesses across the case study countries (RES4AFRICA Foundation 2023). Across the cases, we see that favorable tax policies can reduce costs and make services more affordable, while equipment standards help ensure the safety and reliability of the technologies.

5.5. Nature and sequence of funding support

Secure funding support underpinned achievements in each case, despite chronic funding shortfalls for off-grid energy access in SSA, and a challenging global fundraising environment (Sustainable Energy for All and Climate Policy Initiative 2021, 60_decibels 2024). The initiatives studied here used a combination of grants, equity, debt, and carbon financing to finance their ventures. For instance, SunCulture strategically engaged with a variety of investors, incorporating grant financing for pilot projects, angel investments during the start-up phase, and both debt and equity financing for diverse business operations. It also secured grants from the Renewable Energy and Energy Efficiency Partnership. Similarly, KopaGas has followed a traditional growth funding pathway, with its technology development initially supported by donor grant funds, followed by social and impact investment prior to Circle Gas' acquisition that permitted an early exit from impact investors (ESMAP 2022, MECS, Energy 4 Impact 2022, Circlegas 2023). Unlike most clean cooking companies, KOKO Networks has scaled without public funding. Many of these initiatives attracted substantial corporate investment, proving that private investors are willing to back innovative companies with strong business models even in nascent markets. In some of these cases, the carbon financing secured served as a source of subsidy (Serafeim *et al* 2024). Specifically, for KOKO Networks, carbon finance revenues helped lower the cost of stoves by ∼85% and fuel by ∼25%–40%, to provide consumer subsidies in the order of USD 100 million (CCA 2022, Osiolo *et al* 2023).

Having identified common elements contributing to the achievements of these cases and their importance for future scaling, we briefly mention key limitations of the study. The limited number of case studies included, the restricted set of information available on each case, and challenges on drawing consistent information from across the cases, limits our findings. Even so, our insights offer opportunities for peer-to-peer learning among entrepreneurs, policymakers and investors and point to important directions for future work.

Deepening pro-poor innovation capabilities to extend energy access and improve energy efficiency in the region requires a focus on the full innovation chain, including both products and processes, and with a special emphasis on affordable and convenient delivery of energy services. Though the insights gained from the examination of these case studies are not exhaustive, they do point to specific lessons that may be more broadly applicable, consistent with policy recommendations that success stories can be transferred and adapted, accounting for country contexts (IEA 2023). They also point to the need for additional studies of innovations to expand energy services access from a broader range of country contexts and considering different energy end-uses. While frameworks like the ETIS exist and can be applied to such case studies, these may need to be tweaked and expanded to account for the specific circumstances and challenges of reaching low-income customers in resource poor environments.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

60 Decibels 2024 Why off-grid energy matters 2024 (available at: https://60decibels.com/insights/why-off-grid-energy-matters-2024/)
Abanikanda E O, Dada J T and Ogunjumo R A 2023 Fiscal deficit in sub-Saharan Africa: a new intuition from the institution and political drivers *PLoS One* **18** e0291150
Abrams L 2018 Unlocking the Potential of Enhanced Rainfed Agriculture vol 39 (Stockholm International Water Institute (SIWI)) (available at: www.siwi.org/wp-content/uploads/2018/12/Unlocking-the-potential-of-rainfed-agriculture-2018-FINAL.pdf)
AfDB 2022 Financing a just transition in Africa: challenges and opportunities *Discussion Paper* (available at: www.afdb.org/sites/default/files/2022/12/09/financing_a_just_transition_in_africa-challenges_and_opportunities_final_1_2.pdf)
AGRA 2014 Africa agriculture status report 2014: climate change and smallholder agriculture in sub-Saharan Africa (Alliance for Green Revolution in Africa (AGRA)) (available at: https://agra.org/wp-content/uploads/2021/03/agra-africa-agriculture-status-report-2014.pdf)
Ameli N, Dessens O, Winning M, Cronin J, Chenet H, Drummond P, Calzadilla A, Anandarajah G and Grubb M 2021 Higher cost of finance exacerbates a climate investment trap in developing economies *Nat. Commun.* **12** 4046
Amuakwa-Mensah S and Surry Y 2022 Association between rural electrification and agricultural output: evidence from sub-Saharan Africa *World Dev. Perspect.* **25** 100392
Annelise G-W, Kammen D M and Haya B K 2024 Pervasive over-crediting from cookstove offset methodologies *Nat. Sustain.* **7** 191–202
ARE, UNIDO, and ITPO 2021 Decentralized Renewable Energy Innovations to Boost Agri-Sector Productivity & Address Global Food System Challenges (Alliance for Rural Electrification) (available at: www.afsiasolar.com/wp-content/uploads/2021/01/ARE-Decentralized-renewable-energy-for-agriculture-2020-01-26.pdf)
Arnold M G 2018 Sustainability value creation in frugal contexts to foster Sustainable Development Goals *Bus. Strategy Dev.* **1** 265–275
AUC, UNECA, AfDB, UNDP-RBA 2022 *Africa Sustainable Development Report 2022* (African Union Commission (AUC), the Economic Commission for Africa (ECA) of the United Nations, the African Development Bank (AfDB) and the United Nations Development Programme-Regional Bureau for Africa (UNDP-RBA))
Bartlett L and Vavrus F 2016 *Rethinking Case Study Research* (Routledge) (https://doi.org/10.4324/9781315674889)
Burney J, Woltering L, Burke M, Naylor R and Pasternak D 2010 Solar-powered drip irrigation enhances food security in the Sudano-Sahel *Proc. Natl Acad. Sci. USA* **107** 1848–1853
Byrne R, Ockwell D, Urama K, Ozor N, Kirumba E, Ely A, Becker S and Gollwitzer L 2014 Sustainable energy for whom? Governing pro-poor, low-carbon pathways to development: lessons from Solar PV in Kenya 2014. The STEPS Centre (University of Sussex) (available at: http://steps-centre.org/wp-content/uploads/Energy-Access-online.pdf)
CCA 2022 2022 Clean cooking industry snapshot (Third. Clean Cooking Alliance) (available at: https://cleancooking.org/wp-content/uploads/2022/05/CCA-2022-Clean-Cooking-Industry-Snapshot.pdf)
Chataway J, Hanlin R and Kaplinsky R 2014 Inclusive innovation: an architecture for policy development *Innov. Dev.* **4** 33–54
Circlegas 2023 Circle gas: about us (Circle Gas (blog)) (available at: https://circlegas.co.uk/about-us/)
Connolly-Boutin L and Smit B 2016 Climate change, food security, and livelihoods in sub-Saharan Africa *Reg. Environ. Change* **16** 385–399
Davis K F, Gephart J A, Emery K A, Leach A M, Galloway J N and D'Odorico P 2016 Meeting future food demand with current agricultural resources *Glob. Environ. Change* **39** 125–132
Efficiency for Access Coalition 2021 *Business Model Innovations Addressing Affordability: Case Studies* (available at: https://efficiencyforaccess.org/publications/business-model-innovations-project)
ESMAP 2022 The state of access to modern energy cooking services | ESMAP (available at: www.esmap.org/the-state-of-access-to-modern-energy-cooking-services)
Falchetta G 2021 Energy access investment, agricultural profitability, and rural development: time for an integrated approach *Environ. Res.: Infrastruct. Sustain.* **1** 033002
Falchetta G, Pachauri S, Byers E, Danylo O and Parkinson S C 2020 Satellite observations reveal inequalities in the progress and effectiveness of recent electrification in sub-Saharan Africa *One Earth* **2** 364–379
Falchetta G, Semeria F, Tuninetti M, Giordano V, Pachauri S and Byers E 2023 Solar irrigation in sub-Saharan Africa: economic feasibility and development potential *Environ. Res. Lett.* **18** 094044
FAO, IFAD 2021 The state of food security and nutrition in the world 2021: transforming food systems for food security, improved nutrition and affordable healthy diets for all *The State of Food Security and Nutrition in the World (SOFI) 2021* (FAO) (https://doi.org/10.4060/cb4474en)
FAO, IFAD, UNICEF, WFP and WHO 2023 *The State of Food Security and Nutrition in the World 2023. Urbanization, Agrifood Systems Transformation and Healthy Diets across the Rural–Urban Continuum* (FAO) (https://doi.org/10.4060/cc6550en)
Figuères C 2013 Innovation and Technology for Poverty Eradication pp 1–20
Foster C and Heeks R 2013 Conceptualising inclusive innovation: modifying systems of innovation frameworks to understand diffusion of new technology to low-income consumers *Eur. J. Dev. Res.* **25** 333–355
G7 Italia 2024 2024 G7 climate, energy and environment ministers' meeting communiqué (available at: www.g7italy.it/wp-content/uploads/G7-Climate-Energy-Environment-Ministerial-Communique_Final.pdf)

Gallagher K S, Grübler A, Kuhl L, Nemet G and Wilson C 2012 The energy technology innovation system *Annu. Rev. Environ. Resour.* **37** 137–162

Gebreslassie M G, Bahta S T, Mulugetta Y, Mezgebe T T and Sibhato H 2023 The need to localize energy technologies for Africa's post COVID-19 recovery and growth *Sci. Afr.* **19** e01488

Gerard G, McGahan A M and Prabhu J 2012 Innovation for inclusive growth: towards a theoretical framework and a research Agenda *J. Manage. Stud.* **49** 661–683

Gillespie J 2020 Circle gas and Safaricom extend strategic collaboration (Circle Gas (blog)) 9 September 2020 (available at: https://circlegas.co.uk/circle-gas-and-safaricom-extend-partnership/)

Goedde L, Ooko-Ombaka A and Pais G 2019 Winning in Africa's agricultural market (McKinsey & Company) (available at: www.mckinsey.com/~/media/McKinsey/Industries/Agriculture/Our%20Insights/Winning%20in%20Africas%20agricultural%20market/Winning-in-Africas-agricultural-market.pdf)

Grubler A and Wilson C (eds) 2014 *Energy Technology Innovation—Learning from Historical Succeses and Failures* (Cambridge University Press) Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria

Gumbe L O 2020 Agricultural mechanisation for modernisation of African agriculture *1. ASABE Paper No.* 2001610 (ASABE) (https://doi.org/10.13031/aim.202001610)

Hillocks R J 2014 Addressing the yield gap in sub-Saharan Africa *Outlook Agric.* **43** 85–90

IEA 2023 *A Vision for Clean Cooking Access for All: world Energy Outlook Special Report* (International Energy Agency) (available at: www.iea.org/reports/a-vision-for-clean-cooking-access-for-all)

IEA, IRENA, UNSD, World Bank, WHO 2024 *The Energy Progress Report 2024* (World Bank)

IRENA, and FAO 2021 *Renewable Energy and Agri-Food Systems: Advancing Energy and Food Security Towards Sustainable Development Goals* (IRENA and FAO) (https://doi.org/10.4060/cb7433en)

Jayne T S, Snapp S, Place F and Sitko N 2019 Sustainable agricultural intensification in an era of rural transformation in Africa *Glob. Food Secur.* **20** 105–113

Kalkanci B, Rahmani M and Beril Toktay L 2019 The role of inclusive innovation in promoting social sustainability *Prod. Oper. Manage.* **28** 2960–2982

Kammen and Jacobs 2014 Solar innovation and market feedback: solar photovoltaics in rural Kenya *Energy Technology Innovation* vol 244 (Cambridge University Press)

Koko Fuel Solution 2023 Koko fuel solution—ethanol cooker & ethanol cooking stoves in Africa (KOKO Networks | Technology for Life in the World's Fastest-Growing Cities (blog)) (available at: https://kokonetworks.com/koko-fuel/)

Maritz J 2022 Nigeria: entrepreneur sees opportunity in off-grid freezers *How We Made It in Africa* (available at: www.howwemadeitinafrica.com/nigeria-entrepreneur-sees-opportunity-in-off-grid-freezers/147209/) (15 September 2022)

MECS, Energy 4 Impact 2022 *Modern Energy Cooking: review of the Funding Landscape* (available at: https://mecs.org.uk/wp-content/uploads/2022/02/MECS-Landscape-report_final-17-02-2022.pdf)

Mperejekumana P, Shen L, Saad Gaballah M and Zhong S 2024 Exploring the potential and challenges of energy transition and household cooking sustainability in sub-Sahara Africa *Renew. Sustain. Energy Rev.* **199** 114534

Nain A and Bhasin S 2022 Making sustainable cooling in India affordable *Issue Brief* (Council on Energy, Environment and Water)

Ndunguru E M 2021 Increasing access to clean cooking: the practicality of pay-go in promoting adoption of bottled gas in Kinondoni, Dar Es Salaam, Tanzania *Int. J. Clean Coal and Energy* **10** 41–58

Ockwell D and Byrne R 2016 *Sustainable Energy for All: Innovation, Technology and pro-Poor Green Transformations* (Routledge) (https://doi.org/10.4324/9781315621623)

Osiolo H H, Marwah H and Leach M 2023 The emergence of large-scale bioethanol utilities: accelerating energy transitions for cooking *Energies* **16** 6242

Perros T, Tomei J and Parikh P 2024 Stakeholder perspectives on the future of clean cooking in sub-Saharan Africa and the role of pay-as-you-go LPG in expanding access *Energy Res. Soc. Sci.* **112** 103494

Prahalad C K 2012 Bottom of the pyramid as a source of breakthrough innovations *J. Prod. Innov. Manage.* **29** 6–12

RES4AFRICA Foundation 2023 Africa's energy future is renewable (available at: https://res4africa.org/wp-content/uploads/2023/06/Africas-Energy-Future-is-Renewables-Flagship2023.pdf)

Rosa L, Rulli M, Frankel Davis K, Danilo Chiarelli D, Passera C and D'Odorico P 2018 Closing the yield gap while ensuring water sustainability *Environ. Res. Lett.* **13** 104002

Sagar A D, Mathur A, Birol F, Mulugetta Y, Ogunbiyi D, Sokona Y and Steiner A 2023 Mission energy access for a just and sustainable future for all *Nat. Energy* **8** 1–3

Sennoga E and Balma L 2022 Fiscal sustainability in Africa: accelerating the post-COVID-19 recovery through improved public finances *Afr. Dev. Rev.* **34** S8–33

Serafeim G, Sikochi S and Arora N 2024 *KOKO Networks: Bridging Energy Transition and Affordability with Carbon Financing* (Harvard Business Review)

Smith A, Fressoli M and Thomas H 2014 Grassroots innovation movements: challenges and contributions *J. Clean. Prod.* **63** 114–124

Space in Africa 2020 Koolboks: using geospatial technology and solar power to provide sustainable refrigeration in Africa (Space in Africa (blog)) (available at: https://africanews.space/koolboks-using-geospatial-technology-and-solar-power-to-provide-sustainable-refrigeration-in-africa/) (Accessed 16 December 2020)

Sustainable Energy for All, and Climate Policy Initiative 2021 Energizing finance: understanding the landscape (available at: www.seforall.org/publications/energizing-finance-understanding-the-landscape-2021)

The Leafy Agenda 2021 Challenging the giants: the remarkable story Pf Koko fuel (The Leafy Agenda (blog)) (available at: https://theleafyagenda.co.ke/2021/07/03/challenging-the-giants-the-story-of-koko-fuel-koko-networks/) (3 July 2021)

Thomas A H 2020 Improving crop yields in sub-Saharan Africa—What does the East African data say *IMF Working Papers* (IMF) (available at: www.imf.org/en/Publications/WP/Issues/2020/06/12/Improving-Crop-Yields-in-Sub-Saharan-Africa-What-Does-the-East-African-Data-Say-49477)

UN, Independent Group of Scientists appointed by teh Secretary-General 2023 *Global Sustainable Development Report 2023: Times of Crisis, Times of Change: Science for Accelerating Transformations to Sustainable Development* (available at: https://sdgs.un.org/sites/default/files/2023-09/FINAL%20GSDR%202023-Digital%20-110923_1.pdf)

USAID 2021 SunCulture final report (available at: https://pdf.usaid.gov/pdf_docs/PA00Z2QC.pdf)

Wilson C, Grubler A, Bento N, Healey S, De Stercke S and Zimm C 2020 Granular technologies to accelerate decarbonization *Science* **368** 36

Xie H, Ringler C and Md Alam Hossain M 2021 Solar or diesel: a comparison of costs for groundwater-fed irrigation in sub-Saharan Africa under two energy solutions *Earth's Future* **9** e2020EF001611

Zhao W, Yin C, Hua T, Meadows M E, Yan L, Liu Y, Cherubini F, Pereira P and Bojie F 2022 Achieving the sustainable development goals in the post-pandemic Era *Humanit. Soc. Sci. Commun.* **9** 1–7