Life cycle assessment of renewable energy business models in Africa

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Abstract

Circular business models are increasingly gaining research interest to explore their potential in creating and delivering environmental value. Presently, companies are compelled to operate more sustainably by integrating environmental considerations into their business models. Business model innovation is instrumental to this end. This research aims to improve the understanding of the potential of business models, designed for environmental sustainability, in mitigating the negative impacts of renewable energy development in Africa. Africa is projected to lead globally in new renewable energy additions by 2030 if it meets its nationally determined contributions to the Paris Agreement. Business models will be among the key drivers of this growth, therefore, it is essential to investigate the environmental impacts of production, distribution, and consumption of renewable energy on the continent.

The findings of systematic literature reviews show that so far, the environmental impacts of renewable energy business models in Africa are largely unexplored. There is scarce evidence and a poor understanding of the role and relevance of business models in mitigating the impacts of renewable energy development on a life cycle basis. This research integrates life cycle assessment, participatory decision making, and business model innovation to create an iterative framework for assessing the Environmental impacts of BUsiness Models (EBuM) considering social and economic aspects. It conducts workshops in solar energy companies in Kenya to test the framework and evaluate how incumbent traditional business models can be made more circular to improve their environmental performance. Empirical investigations find that transitioning from traditional to circular business models can significantly reduce life cycle environmental impacts. For example, climate change potential can reduce by 25%-55%. These potential environmental benefits are contingent on customer acceptance of circular business models (e.g., new value propositions) and the financial feasibility of adopting them.

This study makes significant contributions to the wider literature on the topic by providing insights into the environmental impacts of renewable energy development in Africa. It draws from a broad range of evidence to explain why renewable energy business models on the continent fail or succeed and provides key lessons that are beneficial to businesses and policy. This study applies the EBuM framework to present the first life cycle assessment of renewable energy business models in Africa. The framework can be applied to different types of business models across any sector.

List of acronyms and abbreviations

AP	Acidification potential
C_6Cl_6	Hexachlorobenzene
CCP	Climate change potential
CE	Circular economy
CFC	Chlorofluorocarbon
$CHCIF_2$	Chlorodifluoromethane
CO_2	Carbon dioxide
Cu	Copper
EBuM	Environmental analysis of business models
EP	Eutrophication potential
EPC	Engineering procurement and construction
ETP	Ecotoxicity potential
FDP	Fossil depletion potential
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
HCFC	Hydrchlorofluorocarbon
H_2SO_4.	Sulfuric acid
HTCP	Human toxicity carcinogenic potential
HTNCP	Human non-carcinogenic toxicity potential
kW	Kilowatt
kWh	Kilowatt-hour
IRP	Ionising radiation potential
LCA	Life cycle assessment
LUP	Land use potential
m^2	Square metre
MDP	Mineral depletion potential
METP	Marine ecotoxicity potential
Mg	Milligram

NH_3	Ammonia
NH_4^+	Ammonium
N_2O	Nitrous oxide
NO	Nitric acid
NO_x	Nitrogen oxide
NO_3	Nitrate
ODP	Ozone depletion potential
PO_4^{3-}	Phosphate
POFPHH	Photochemical ozone formation, human health potential
POFPET	Photochemical ozone formation, terrestrial ecosystem potential
PMFP	Particulate matter formation potential
PV	Photovoltaic
PSS	Product service system
SHS	Solar home system
SI	Supporting information
SO_3	Sulfur trioxide
SODP	Stratospheric ozone depletion potential
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
WDP	Water depletion potential;
Wp	Watt peak
µg	Microgra

Declaration Statement

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

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Chapter 1: Introduction

The emphasis on clean energy transition for a net-zero future has been gaining momentum (e.g., IEA, 2021a; IEA, 2021b; OECD, 2021). However, the transition is not without hurdles in low-income countries due to the technical, social, and financial challenges of implementing low-carbon technologies (Lowitzsch, 2019). Besides, environmental degradation further increases the complexity of attaining and sustaining a clean energy transition (Nevshehir, 2021), which is counter-productive to the strides made to increase renewable energy generation. Particularly so for Africa, which has the potential to lead globally in new installed capacity additions by 2030 (IRENA, 2019) and, subsequently, a corresponding increase in negative environmental impacts.

A technology-focused approach to mitigating the environmental impacts of well-established renewable energy systems is likely to be incremental, rather than significantly transformational, due to their technological maturity. Besides, most of these technologies are widely adopted in commercial, industrial, and residential sectors across the region. Thus, incremental innovations to mitigate the environmental impacts of products that are already in circulation may not be significantly effective.

This research explores how business models contribute to the environmental impacts of renewable energy development and ways they can be designed to mitigate these impacts. This line of enquiry is chosen because the potential of business model innovation in achieving significant reductions in the negative environmental impacts of renewable energy development is underresearched. A business model is defined as the justification of firms creating and delivering value to customers for financial gain (Magretta, 2002). Girotra and Netessine (2013) confirm that business models can be innovated to adopt products and services that encourage sustainable use of resources by identifying inefficiencies in existing business models. Inefficiencies can occur anywhere along the value chain when business decisions are (i) based on incomplete or inaccurate information (e.g., on the performance of technology) and (ii) misaligned with the objectives of the value chain (e.g., the unwillingness of manufacturers to take part in take-back schemes) (ibid). Understanding these inefficiencies is important in resolving environmental sustainability issues in business models and translating them to other contexts.

Business model innovation can create sustainable business models, whose value propositions integrate and deliver on ecological, economic, and social sustainability (Boons and Lüdeke-Freund, 2013). It is recommended among other tools such as industrial symbiosis, supply-chain management, and eco-design to guide the assimilation of environmental sustainability into business models (Reichel et al., 2016). Their relevance in mitigating environmental impacts is perhaps even more significant because the successful diffusion of renewable energy technologies depends on the business models that implement them.

Business model innovation alone does not necessarily bring about improved environmental outcomes. It should be evaluated using tools such as life cycle assessment (LCA), which quantify the environmental impacts of product-systems and have been tested on sustainable business models (e.g., Martin et al., 2021; Sassanelli et al., 2019). Related to this, business models for the circular economy (CE) can be designed for environmental sustainability through dematerialisation, product life extension, waste reduction, and resource efficiency (Bocken et al., 2016).

CE can be achieved by (i) creating long-lasting products to narrow loops; (ii) adopting servitisation, sharing models, repairs, and maintenance to slow loops; (iii) digitalisation; and (iv) reusing, recycling, refurbishing, and remanufacturing to close loops (Geissdoerfer et al., 2020). Circular business models are types of sustainable business models (Bocken et al., 2014) and primarily focus on monetary and non-monetary social, environmental, and economic aspects. For example, preventing or reversing premature obsolescence (Hollander and Bakker, 2016) and closed-loop supply chains to utilise the economic value in products after their first life (Linder and Williander, 2017; Roos, 2014). These business models require the alignment of stakeholders' incentives along the value chain (Geissdoerfer et al., 2018) i.e., fair distribution of costs, risks, and benefits among all stakeholders in the network (Narayanan and Raman, 2004). The success of circular business models also depends on customers' interests, attitudes, and willingness-to-pay the cost attached to sustainable products and services (Kazeminia et al., 2016; Mentink, 2014). Besides, awareness of ethical and environmental issues, personal characteristics (e.g., income or education), and perceived social and functional values affect customers' purchase intentions towards circular business models (Mostaghel and Chirumalla., 2021).

Other than customer buy-in and stakeholder alignment, the commercial viability of circular business models is affected by the knowledge of closed-loop recycling within organiations, legal and administrative aspects of contractual agreements, investment cost, the circularity of the supply chain, policies and legislations, and the market price of alternative products, etc (Vermunt et al., 2019).

The potential benefits of CE and circular business models have been critiqued on matters such as the feasibility of a completely closed-loop system (Corvellec et al., 2022) and the implementation hurdles of displacing primary production with secondary materials (e.g., Zink and Geyer, 2017). There are critiques about uncertainties of the actual environmental benefits of CE. For example, in some cases, e.g., recycling plastics, large quantities of secondary materials are required to substitute primary production which in turn increases the demand for landfill space (Dace et al., 2014). The CE system is perceived as complex, comprising a hierarchy of actors whose functions will need to diversify or change in line with the changing flow of materials and information (e.g., Castro et al., 2022). Several studies found that business models which follow the CE logic can be beneficial (Mont, 2004) or damaging (Corvellec and Stål, 2017) to the environment depending on the extent to which they deliver CE principles of narrowing, slowing, and closing resource loops. Circular business models do not always have superior environmental performance to linear business models (Brandão et al., 2020). A case-by-case analysis of circular business models is required to ascertain whether they can deliver environmental benefits.

Perspectives from the Global South are barely included in CE literature (Brandão et al., 2020). The application in the renewable energy sector in Africa is particularly limited and underresearched in practitioner and academic literature (Mutezo and Mulopo, 2021). Thus, the potential of circular business models in the region is not fully understood (Desmond and Asamba, 2019). This type of assessment is required to not only contribute to the broader literature on the topic but also provide insights into the potential of CE from the standpoint of companies implementing traditional business models.

1.1 Research motivation and strategy

This research aims to quantify the environmental impacts of renewable energy business models in Africa and evaluate the potential of business model innovation in achieving improved outcomes. This research brings together two different research areas (i.e., business model analysis and life cycle assessment) to investigate the research problem and create new solutions that may not be completely addressed within the scope of individual disciplines. It seeks to give a better understanding of the environmental impacts of renewable energy development in Africa and the business models that bring about the development. It also brings together LCA and business model innovation to establish how business models can cause and mitigate environmental impacts. To this end, it creates a novel framework that can be used by companies to evaluate the environmental performance of their business models.

The *first* objective of this research is to perform a systematic literature review of the environmental impacts of renewable energy in Africa (Paper 1 ; Chapter 2 in this manuscript). Paper 1 evaluates the status of LCA research and whether it is uniquely different from other regions. The paper titled 'life cycle assessment of renewable energy in Africa' synthesises information to generate reliable evidence on the topic to influence decision-making. The investigation found that the LCA of renewable energy in Africa is mainly performed for the technology as discussed in detail in the literature review but excludes analysis of business models. The paper also highlights methodological issues of conducting LCA of renewable energy in Africa and ways of avoiding them. Paper 1 confirms that indeed the environmental impacts of renewable energy in Africa are significant. It also provides the groundwork for building research on business models which are the core of renewable energy development.

The *second* objective of this research is to perform a systematic literature review of renewable energy business models in Africa to provide insights into their social, economic, and environmental sustainability (Paper 2; Chapter 3 in this manuscript). The paper titled 'a review of business models for access to affordable and clean energy in Africa: do they deliver social, economic, and environmental value?' highlights the main characteristics of the business models. This study analyses factors affecting the viability of these business models and their sustainability orientation, underscoring the need for introducing a life cycle outlook in future studies.

Following a classification proposed by (Richter, 2012) business models in this thesis are broadly categorised as customer-side if they implement renewable energy systems that are constructed on or near the customers' property or utility-side for large-scale systems that supply electricity to the grid. Several archetypes of customer-side business models are identified. The rent-to-own business model sells small renewable energy technologies (e.g., solar lanterns) to customers on a pay-as-you-go basis to reduce the affordability barrier. Customers pay regular installments for using the systems until the purchase price is covered after which they assume ownership. The renting and leasing business model allows customers to use renewable energy technologies for a limited time, based on contractual agreements. Energy companies retain ownership of these technologies and provide maintenance and repair services. In the pay-per-service business model archetype, customers pay for using electricity from renewable energy technologies. Energy companies construct electricity generation infrastructure and distribution networks and supply electricity to households, businesses, and institutions. Other customer-side business model archetypes include prosumer where energy consumers own renewable energy systems constructed on their property. These consumers sell surplus electricity to the grid based on the terms of power purchase agreements. In the engineering procurement and construction (EPC) model, companies design, purchase, and construct renewable energy systems and sell them to customers as turnkey projects.

Customer-side business models for bioenergy systems identified in this study mainly describe various farming models for feedstock production. For example, farmers in smallholder and independent large-scale farming models cultivate energy crops and sell them to bioenergy companies. Outgrower schemes are contractual farming models between farmers and bioenergy companies contingent on feedstock delivery and purchase agreements. In plantation farming models, bioenergy companies acquire large tracts of land on a concession or lease basis and grow energy crops. A hybrid model comprises both smallholder and large-scale farming where both parties own land for energy crop production. Archetypes of utility-side business models are EPC for large-scale renewable energy infrastructure. Owners of the infrastructure become independent power producers who enter into off-take agreements with the utility.

The systematic literature reviews identify under-researched areas in LCA and business model literature. The reviews were structured and systematic in the sense that studies were systematically analysed to derive themes, classifications, and information to answer specific research questions. The research questions were formulated to identify keywords and synonyms that were used to identify publications in bibliographic databases such as Scopus, Google Scholar, and Web of Science. The review was performed in three main steps. First, keyword search strings were used to identify relevant studies on the life cycle assessment of renewable energy in Africa and renewable energy business models in Africa. Second, the studies that came up were screened using the following inclusion criteria (i) peer-reviewed studies, (ii) studies published in English, and (iii) studies that explicitly cover the life cycle of renewable energy technologies and business models in Africa to select the final sample. The rejection criteria included (i) studies not published in English, (ii) Masters and PhD thesis and institutional reports, (iii) studies that were not conducted in the African context, and (iv) studies that did not explicitly address the research topic. Third, data extraction tables were used to systematically obtain information about renewable energy systems, applications, country of study, life cycle steps, and business model types and archetypes. The systematic approach was useful in classifying business models and analysing the LCA process. As will be discovered from the systematic literature reviews, LCA and business models are distinct research areas that are not paired in current studies. Therefore, the extent to which they complement each other and their combined effect is undocumented.

The *third* objective of this research is to create a new framework that can be used to quantify the Environmental impacts of BUsiness Models (EBuM framework) and test it on solar energy companies (Paper 3; Chapter 4 in this manuscript). The EBuM framework integrates LCA, the business model innovation, and participatory decision-making to create a comprehensive analytical framework. LCA was performed following ISO 14044:2006 and ISO 14044:2006 guidelines (ISO 2006a, b). The LCA framework comprises four sequential steps i.e., goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. The goal describes the purpose of the study and its intended use. It also defines the functional unit considering the function of the system under study. The scope determines which life cycle stages and processes are included in the study. The life cycle inventory lists the inflows into a system (i.e., materials, products, and resources) and outflows (i.e., valuable products, emissions, and waste). Foreground data were obtained from renewable energy companies while the Ecoinvent database version 5 was the source of background data. The impact assessment step translates the inflows and outflows of a product system into potential environmental impacts. The ReCiPe impact assessment methodology was used in this study to calculate the following 18 midpoint impact categories:

- Climate change potential (CCP): refers to the emission of greenhouse gases such as CO_2, CH_4, N_2O, NO, NO_2, SF_6, and halocarbons such as chlorinated fluorocarbons. Global warming potential is expressed in kg CO_2 eq.
- Stratospheric ozone depletion potential (SODP): results from the emission of ozone-depleting substances such as chlorofluorocarbons, hydrobromofluorocarbons, hydrochlorofluorocarbons, bromochloromethane, halons, methyl chloride, methyl bromide, carbon tetrachloride, and tetrachloromethane. Stratospheric ozone depletion potential is expressed as kg CFC11 eq.
- Ionising radiation potential (IRP): it is caused by the emission, dispersion, and exposure to radionuclides and is expressed as kBq CO-60 eq. It causes negative impacts on human health such as an increase in hereditary defects and cancer.
- Photochemical ozone formation, human potential (POFPHH): it is caused by photochemical reactions from the emission of non-methane volatile organic compounds and NO_x from activities such as transport, industrial processes, and the use of organic solvents, among others. NO_x is emitted from incineration facilities and engines because of the incomplete combustion of fuels. Ozone formation causes respiratory complications in humans. It is expressed as kg NO_x eq.
- Photochemical ozone formation, terrestrial ecosystems potential (POFPTE): the causes are the same as photochemical ozone formation human health. Ozone formation also affects terrestrial ecosystems e.g., plant productivity (i.e., low seed production and resilience to stressors). It is expressed as kg NO_x eq.
- Particulate matter formation potential (PMFP): it falls under the category of toxicity-related health effects in the sense that it contributes to diseases in humans from exposure to organic and inorganic particles, NH_4, NO_x, SO_x, volatile organic compound, nitrates, sulphates, and organic carbonaceous matter. Particulate matter formation is expressed as kg $PM_{2.5}$ eq.
- Terrestrial acidification potential (TAP): expressed as kg NO_x eq, terrestrial acidification potential refers to a decrease in the neutralising capacity of terrestrial ecosystems (e.g., soil) causing them to become acidic. Acidification in soils increases in two ways (i) displacement and leaching of cations by the addition of hydrogen ions in soil and (ii) uptake of cations by plants followed by harvesting or extraction. Acid rain which is formed by the reaction of hydrogen and water in the atmosphere is a common cause of acidification. Some of the sources of acidifying compounds are

SO_x, NO_x, NH_4, hydrochloric acid (HCl) and, sulphuric acid (H_2SO_4). The extent of soil acidification depends on the nature of the soil and geology.

- Freshwater eutrophication potential (FEP): eutrophication is nutrient enrichment and is expressed as kg P eq. The main contributors to eutrophication are nitrogen and phosphorus. Effects of freshwater eutrophication include algal bloom, altered aquatic species composition, growth of invasive species, stratification and decrease in dissolved oxygen, reduction in biodiversity, and degradation of water quality.
- Marine eutrophication potential (MEP): it has similar causes and effects as freshwater eutrophication. Unlike freshwater, nitrogen is often the limiting nutrient. Marine eutrophication potential is expressed as kg P eq.
- Terrestrial ecotoxicity potential (TETP): ecotoxicity covers the exposure of terrestrial, freshwater, and marine ecosystems to chemicals, mobility of the toxic substances, the persistence of the chemicals in the environment, and damage to ecosystems. A chemical substance that has a short lifespan and undergoes low mobility may have a low toxicity impact compared to one with a long lifespan and low mobility. Sources of chemical emissions are numerous i.e., nearly all processes in the inventory. Terrestrial ecotoxicity relates to exposure and damage to non-aquatic ecosystems and is expressed as kg 1,4-DCB.
- Freshwater ecotoxicity potential (FETP): refers to chemical exposure and damage to freshwater ecosystems and it follows the same principles discussed under terrestrial ecotoxicity. Freshwater ecotoxicity potential is expressed as kg 1,4-DCB.
- Marine ecotoxicity potential (METP): refers to chemical exposure and damage to marine ecosystems and it follows the same principles discussed under terrestrial ecotoxicity. An increase in metals such as copper, cobalt, zinc, and manganese increases marine ecotoxicity. Marine ecotoxicity potential is expressed as kg 1,4-DCB.
- Human carcinogenic toxicity potential (HTCP): it follows the same principles as ecotoxicity i.e., emitted quantity, mobility, persistence, exposure patterns, and damage. Human carcinogenic toxicity measures the potential impact of increased cancer risks from exposure to carcinogens. Human carcinogenic toxicity potential is expressed as kg 1,4-DCB.
- Human non-carcinogenic toxicity potential (HTNCP): it is similar to human carcinogenic toxicity potential only that it relates to non-cancer risks. Human non-carcinogenic toxicity potential is expressed as kg 1,4-DCB.

- Land use potential (LUP): land transformation is the conversion of land from one state to another while land occupation is the use of land for a given purpose. Changes in land use can impact the quality and function of ecosystems, disrupt ecosystem services, change hydrological cycles, lead to loss of biodiversity, increase soil erosion, and change local and regional climate among other impacts. The magnitude of impacts of land use depends on the quality of soil, topography, climate, and ecological quality. Land use potential is expressed as m^2 a crop eq.
- Mineral depletion potential (MDP): this impact category covers abiotic non-renewable resources such as metals, fossil fuels, and minerals. Mineral resource scarcity is brought about by consumptive and dispersive resource uses. The former refers to the irreversible transformation of resources to a state that leads to loss when the resource is used e.g., fossil fuel combustion, while the latter transforms a resource to a state that allows it to be used without losing it e.g., metals (Rosenbaum et al., 2018). Mineral depletion potential is expressed as kg Cu eq.
- Fossil depletion potential (FDP): it impacts the future availability of fossil fuels and drives up costs associated with using alternative technology to extract fossil fuels from costlier geographical locations or using alternative production methods like enhanced oil recovery. Fossil fuel resources are crude oil, hard coal, natural gas, brown coal, and peat. This impact category is expressed as kg oil eq.
- Water depletion potential (WDP): sources of water include surface water, seawater, rainwater, groundwater, and wastewater. Water use can be a temporary or permanent removal of water from a water body for anthropogenic activities. The water depletion potential impact category analyses the availability and scarcity of water relative to the demand for anthropogenic uses. Water use affects its availability for ecosystems and humans and is expressed as m^3.

Paper 3 titled ‘environmental evaluation of business models: the EBuM framework and its application to solar energy companies in Kenya’ performs a comparative analysis of traditional (i.e., incumbent) and new (i.e., CE) business models. The analysis highlights under which circumstances (variables) traditional business models become circular to improve their environmental performance.

LCA is often performed to evaluate the negative environmental impacts of products and systems (Bjørn et al., 2018) but its application in the analysis of business models is still scarce. A probable reason is that business models facilitate the interaction between social, economic, and environmental aspects and do not straightforwardly fit within the structured approach of the LCA methodology. LCA methodology neither takes into consideration economic aspects such as the value chain interactions nor most socio-technical systems of business models (Costa et al., 2019). The main difference between LCA of technologies and business models is the unit of analysis. LCA of technologies focuses on the technology and its life cycle stages. Conversely, in LCA of business models, the technology (which makes up the key resources block of business models) is analysed alongside other blocks to ascertain how interactions in the supply-side, demand-side, value proposition, and financial aspects bring about environmental impacts. Thus, the LCA of business models builds on traditional LCAs by taking the business model as the unit of analysis. Böckin et al. (2022) and Goffetti et al. (2022) add that in LCA of business models, the economic performance should be the grounds for comparison i.e., physical and monetary flows should be quantitatively related and expressed in the functional unit.

In this study, LCA of business models focused on the renewable energy technology (key resources block), life cycle stages (key activities block), and how they relate to other blocks of the business model i.e., value proposition, key partnerships, channels, customer segments, customer relationships, revenue model, and costs. Business model blocks are viewed as the hotspot or drivers of environmental impacts. Hotspots directly cause environmental impacts to occur e.g., technology production on the supply side and use or disposal on the demand side while drivers indirectly contribute to these impacts e.g., consequences of a value proposition or financial considerations. The characteristics of business models for renewable energy vary considerably in terms of their function, technology composition, product ownership, product lifetime, etc. Therefore, LCA findings, interpretation, and recommendations should be evaluated on a case-by-case basis. The findings of the systematic literature reviews and empirical research can be combined to evaluate the social, economic, and environmental factors that might promote or impede business model innovation and the adoption of circular business models. The key research questions for this project based on the objectives discussed above are as follows:

RQ1: What are the environmental impacts of, and the status of LCA research on renewable energy in Africa?

RQ 2: What types of business models for renewable energy are adopted in Africa and to what extent do they create social, economic, and environmental value?

RQ3: How can LCA be applied in the analysis of business models?

RQ4. How can business model innovation and circular economy be leveraged to mitigate the environmental impacts of traditional business models?

1.2 Thesis structure

The rest of this thesis is structured as follows:

- Chapter 2 presents a systematic literature review of the LCA of renewable energy in Africa. The paper has been published in the journal of Sustainable Production and Consumption and, thereby, presented according to the journal's guidelines.
- Chapter 3 presents a systematic literature review of renewable energy business models in Africa. The paper has been published in the journal of Energy Research and Social Science and, thereby, presented according to the journal's guidelines.
- Chapter 4 presents an original research article on the LCA of solar energy business models in Kenya. The paper has been submitted for publication.
- Chapter 5: Discussion discusses the key research questions given the findings of the three papers. It also gives the implications of the research to industry and policy and highlights the contribution of this research.
- Chapter 6 gives the main conclusion, limitations of this research and future research needs.

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Chapter 2

Paper 1: Life cycle assessment of renewable energy in Africa

This paper was published in the journal of Sustainable Production and Consumption. It was prepared according to the guidelines of the journal.

Mukoro, V., Gallego-Schmid, A. & Sharmina, M. (2021). ‘Life cycle assessment of renewable energy in Africa’, *Sustainable Production and Consumption,* 28, 1314-1332. Available at: https://doi.org/10.1016/j.spc.2021.08.006

This paper performs a systematic literature review of the environmental impacts of renewable energy in Africa. Sections, figures, and tables have been renumbered to comply with the structure of this thesis. The doctoral researcher (Velma Mukoro) is the lead author of this paper. Her contributions to the paper are the conception of the study, providing ideas, acquiring and processing data, analysis, interpretation, writing, and revising the paper. The co-authors’ (Dr Alejandro Gallego-Schmid and Dr Maria Sharmina who are the lead author’s supervisors) contributions are the conception of the study, critical revisions of the paper, and editing the final version for publication.

Abstract

Renewable energy capacity in Africa is expected to reach 169.4 GW by 2040 from 48.5 GW in 2019. The growth of the sector necessitates a reevaluation of the environmental impacts of renewable energy on the continent to inform mitigation decisions. This study presents the first literature review of the life cycle assessments of renewable energy in Africa and gives an in-depth analysis of environmental issues that are specific to Africa’s renewable energy sector. It performs a systematic assessment of literature on the topic, examines the state-of-the-art, and critically evaluates environmental impacts on the continent, implications of methodological choices, gaps, challenges, and compares the findings with other regions. Climate change has been extensively researched in the studies, due to decarbonisation being among policy priorities. Other relevant impact categories such as resource depletion, ecotoxicity, ecosystem degradation from wase treatment are not fully explored despite the end-of-life being potentially a major burden for the continent. Choice of functional units and multifunctional processes give wide variations in the magnitude of environmental impacts for similar technologies and, therefore, have implications for decision-making. For example, similar biodiesel jatropha systems with energy- and mass-based functional units differ by around 16% in their climate change potentials. To ensure that life cycle assessment results apply to mitigation decisions in Africa, studies should consider methodological issues such as lack of transparency in inventories, incomplete coverage of life cycle stages and impact categories, and missing databases adapted for the African context.

Keywords

Renewable energy; Environmental impacts; Climate change; LCA; Literature review; Africa

Graphical abstract

2.1 Introduction

Renewable energy is one of the key decarbonisation pathways to net-zero alongside energy efficiency, carbon capture and storage, and behavioural change (IEA, 2021a). Beyond decarbonisation, the socio-economic benefits of renewable energy span safeguarding energy security, narrowing the energy access gap, particularly in low-income countries, and reducing energy-related health complications caused by indoor air pollution. The global renewable energy generation capacity is projected to reach 8,300 TWh in 2021, which is a more than 7% increase from 2020 following the decline in fossil fuel use at the outset of COVID-19 (IEA, 2021b). The increase in renewable electricity generation during the pandemic is attributed to continued new installations globally, low marginal operation costs, and binding power supply contracts from wind and solar energy (ibid; Khanna, 2020) despite disruptions in supply chains, financial challenges, and global lockdown measures that all contributed to delayed construction.

Broadly, renewable energy growth relies on a combination of stringent energy policies at the global scale such as the Paris Agreement, falling costs that are making renewables cost-competitive with some fossil fuels, economic feasibility, ambitious targets, government incentives on renewable energy projects, and market reforms such as phasing out fossil-fuel subsidies (Bogdanov et al., 2019; IEA, 2021a; REN 21, 2019). The resilience of renewable energy during COVID-19, demonstrated by increased generation and usage, can prepare the ground for green economic recovery and sustainable energy transition (Khanna, 2020).

The primary energy demand in Africa in 2018 was largely biomass (49%), followed by oil (23%), natural gas (16%), and coal (13%) while modern renewable energy (e.g., solar, geothermal, wind) constituted 2% (IEA, 2019). The total electricity generated on the continent in the same year was about 240 TWh of which 60% came from renewable sources, mostly hydropower (ibid). The renewable energy sector has continued to grow, particularly in the power sector where the installed capacity increased from 23.5 GW in 2008 to 48.5 GW in 2019 (IRENA, 2020). The renewable energy capacity for Africa will continue to increase rapidly as countries strive to meet targets set out in their Nationally Determined Contributions to the Paris Agreement. The planned generation of renewable energy in Africa by 2040 is 351 TWh for hydropower, 229 TWh for solar photovoltaic (PV), 159 TWh for wind, 59 TWh for geothermal, and 119 TWh for other renewables under existing policy frameworks (IEA, 2019).

The renewable power sector is growing faster than renewables used for heating, cooling, and transportation. Among renewable electricity sources, hydropower is the largest in terms of installed capacity at 35.8 GW, followed by solar, wind, and modern bioenergy (excluding traditional biomass) at 7.4 GW, 5.8 GW, and 1.7 GW, respectively, in 2019 (IRENA, 2020). Renewable heat in Africa is largely supplied by biomass and is mostly used for cooking. Solid biofuel and renewable waste capacity on the continent were estimated to be 1.6 GW in 2019, most of which were produced in South Africa and Ethiopia (IRENA, 2020). Countries like Tunisia and South Africa are leading in solar water heating installations having about 0.6 GW and 1.3 GW, respectively, in 2016 (REN 21, 2018). The uptake of renewable energy for transportation in Africa is still very low, although Angola, Ethiopia, Malawi, South Africa, Sudan, and Zimbabwe have policies in place to integrate between 5% and 15% ethanol in their transport sectors (REN 21, 2020).

Renewable energy is a key pillar for Sustainable Development Goal 7 (SDG7) and has been pivotal to narrowing the energy access gap, particularly in low-income countries. In Sub-Saharan Africa, progress in energy access is also attributed to factors such as energy sector policy reforms, access to finance, market development, and technology innovation (Corfee-Morlot et al., 2019). The electrification rate in Sub-Saharan Africa was about 45% on average in 2019 with significant regional disparities between urban and rural areas, while only 20% of the population has access to clean cooking (IEA et al., 2021; IEA, 2021 a). In addition to national grid extension, decentralised renewable energy technologies such as solar mini-grids, solar home systems, and pico PV systems dominate universal electrification initiatives at different tiers of electricity access defined by the World Bank's multi-tier framework (Bhatia and Angelou, 2015). Solar PV constituted 74% of off-grid renewable energy capacity in Africa in 2019 (IRENA, 2020) serving about 49% of the population in Sub-Saharan Africa (GOGLA, 2021), while traditional bioenergy remains the dominant source of fuel across the region except for South Africa which relies largely on coal (IEA, 2019).

While renewable energy is resolving SDG7 challenges in Africa to a varying extent (i.e., more progress in electricity generation than thermal applications), its contribution to the environmental burden on a life cycle basis should not be overlooked. The magnitude of environmental impacts of renewable energy varies depending on the source, technology, and the life cycle stage of a project (Asdrubali et al., 2015; Dincer and Bicer 2018). The ongoing and, crucially, predicted future surge of Africa's renewable energy capacity necessitates an assessment of the sector from a life cycle perspective. Accordingly, the environmental performance of renewable energy on the continent has been assessed in Life Cycle Assessment (LCA) studies.

For the most part, LCA studies of renewable energy in Africa focus on quantifying environmental impacts, hotspots, and contribution analyses, with a few exceptions investigating life cycle inventories, and economic and social aspects. So far, there are only two peer-reviewed literature reviews of LCA of renewable energy in Africa (Bacenetti et al. 2016; Gerbinet et al. 2014), but they are not exclusive to the continent and only focus on one type of energy source. In particular, Bacenetti et al. (2016) and Gerbinet et al. (2014) review publications on anaerobic digestion and solar PV respectively, in various regions of Africa, Europe, Asia, South America, and North America. A review that exclusively draws from existing studies of life cycle assessments of renewable sources in Africa is missing. Therefore, a broad range of context-specific environmental issues on the continent remain underrepresented, including the consequences of technology applications, the relevance of upstream and downstream activities for the magnitude of impacts, methodological choices that affect LCA results, and opportunities for mitigating environmental impacts in light of the projected growth of the sector.

There are similarities and differences in renewable energy needs, drivers, and challenges between high-, middle-, and low-income countries pertaining to decarbonisation goals, environmental policy priorities, energy access, business models, technology advancements, and costs (Engelken et al., 2016). The similarities and differences across geographical contexts and income levels imply varying magnitudes of environmental impacts and mitigation measures; hence, there is a pressing need for critical and in-depth analyses of LCAs of renewable energy considering regional specificities and income classifications.

This study performs for the first time an in-depth LCA review of renewable energy in Africa to (i) examine the state-of-the-art and critically evaluate environmental impacts of renewable energy, current and future challenges, and mitigation options in light of unprecedented growth of the sector; (ii) discuss the significance of upstream and downstream processes and hotspots; (iii) compare findings with low-, middle-, and high-income countries to provide insights for decision-making at both the micro- and macro-levels; (iv) assess implications of methodological choices and describe regional challenges of LCA; and (v) identify research needs in LCAs of renewable energy in Africa and offer guidance to LCA practitioners and decision-makers in policy and business.

2.2 Method

The authors performed a systematic literature review to identify published studies of LCA of renewable energy in Africa. Keywords searches were performed in Scopus and Web of Science using the following search string combinations:

- "Life Cycle Assessment" AND "renewable energy" AND "Africa".
- "Life Cycle Assessment" AND "renewable energy" AND "name of an African country". The search string for all African countries was performed using the given combination.
- "Life Cycle Assessment" AND "renewable energy" AND "developing countries".
- "Life Cycle Assessment" AND "renewable electricity" AND "developing countries".

The authors cross-checked the search results to remove duplicates and articles whose focus did not address the topic. Table A 1 in Supporting Information (SI) gives a breakdown of the search strings that were performed and the number of articles that came up. One hundred and fifty-seven studies were identified (April 2021). The abstracts of the articles were screened to determine their relevance to the topic and 104 were excluded because they did not explicitly perform an LCA of renewable energy sources in Africa.

Only peer-reviewed and conference papers or articles published in English were considered. For this reason, PhD and masters theses, handbooks, and book chapters were not included. For studies conducted for multiple locations around the world, at least one of the case studies was for an African country. As a final sample, 53 studies were included in this review (Table A 2 in SI) because they met one of the following criteria:

- Studies that perform LCA of renewable energy in Africa following ISO 14040:2006 and ISO 14044:2006 framework (ISO 2006a, b);
- Studies that perform LCA of renewable energy as part of their broad objectives on condition that LCA is adequately discussed and the environmental impacts explicitly attributed to the LCA process;
- Studies that perform life cycle inventory and account for energy, emissions, and material flows.

To identify methodological issues specific to Africa and their impact on the quality of the results, LCA studies were not removed from the sample based on minor or unavoidable flaws in the method, as discussed in detail in the results. Grey literature on LCA of renewable energy in Africa conducted by credible sources such as IPCC (2012) was not included in the sample but was used for comparison and to complement evidence.

2.3 Results and discussion

The findings of this systematic literature review are mostly presented in an aggregated format to facilitate the comparison of different sets of data. Context-specific results are only given where aggregation cannot be performed (e.g., where case studies for a given renewable energy technology are few), for emphasis, or to provide evidence for a claim. For impact categories that are strongly dependent on local or regional conditions, generalisation is avoided.

2.3.1 Types and applications of renewable energy

2.3.1.1 Bioenergy

Among the different renewable energy sources, bioenergy is the most studied in this literature sample (34 articles, excluding hybrid energy systems and studies that analyse multiple renewable energy sources) (Table 1). LCAs of bioenergy in the reviewed studies are for traditional biomass (e.g., wood fuel combustion in energy-efficient stoves), and first and second-generation biofuels (e.g., biodiesel production from transesterification of seed oil and lignocellulosic biomass for electricity production, respectively).

LCAs of liquid biofuels for electricity generation and transport cover oil extraction from jatropha, castor seeds, soybeans, and palm kernels cultivated in rain-fed or irrigated plantations. Studies on solid biofuels cover bagasse, briquettes, wood, and charcoal for heat (e.g., wood combustion in stoves in Kenya and Tanzania (Okoko et al., 2017)) and electricity (e.g., electricity generation from bagasse in Mauritius (Brizmohun et al., 2015; Ramjeawon, 2008)). LCAs on gaseous sources of biofuels are for biogas production from anaerobic digestion from fibrous and non-fibrous feedstock and landfill gas recovery from municipal solid waste. For example, animal dung (Afrane and Ntiamoah, 2011; Lansche and Müller, 2017), poultry manure (Galgani et al., 2014), vegetable and animal waste (Nzila et al., 2012), and putrescible organic components of municipal solid waste (Ayodele et al., 2018; Ayodele et al., 2017) are used as feedstock. Studies on hybrid bioenergy systems, e.g., biomass heat plants coupled with solar thermal systems (i.e., Banacloche et al., 2020; Herrera et al., 2020), and bioenergy alongside other renewable energy sources (i.e., Gujba et al., 2010) are infrequent.

From a sectoral perspective, the LCAs of the reviewed bioenergy studies are mostly for heat and electricity generation (see Table 1) with fewer studies on transport. This finding can be explained by the increasing supply and uptake of biofuels in the heat and power markets in Africa. The transport sector has had the lowest uptake owing to reliance on petroleum products as well as the technical, political, market, and institutional barriers (García-Olivares et al., 2018), which is similar to the situation in industrialised regions, for example in parts of Europe (European Environment Agency, 2018). This finding also reflects the global situation whereby the deployment of renewable transport is still a low priority for policymakers (REN 21, 2018).

No LCA of third-generation and advanced biofuels was found among the studies reviewed. Third-generation and advanced biofuels are mostly in the research and development, pilot and demonstration, and pre-commercial stages and, therefore, not yet deployed in the African market (Stafford et al., 2018). Unlike traditional biomass and first-generation biofuels which constitute higher shares of bioenergy supply and have maturer markets globally, second and third-generation biofuels supply and demand are concentrated in various parts of North America, Europe, Latin America, and the Asia Pacific. Accordingly, most LCAs of bioenergy set in low-income countries are for biodiesel generation from first-generation biofuels (Cherubini and StrØmman, 2011). Studies set in high-income countries span a wide spectrum of feedstocks across generations such as starch crops, sugar crops, oil crops, lignocellulosic crops, waste wood (ibid) although LCAs for microalgae and cyanobacteria are mostly restricted to laboratory experiments, hypothetical genetically engineered scenarios, pilot trials, or less mature technologies (e.g., Collet et al., 2014; Lardon et al., 2009; Nilsson et al., 2020). With research and development, technology advancements, and maturity, future LCAs can explore third-generation biofuels at scale in low-, middle-, and high-income markets and their implications for the food energy crops trade-offs.

Table 1: Renewable energy technologies and sectors of application in the reviewed articles

Technology	Number of studies	Sector (and number of studies)
Liquid biofuel (biomass- *jatropha sp., palm oil, castor oil, soybean*)	17	Thermal (2), power generation (6), power generation and transport (1), transport (6), application not stated (1)
Solid biofuel (plant biomass, bagasse, renewable waste)	10	Thermal (6), power generation (3), application not stated (1)
Gaseous biofuel (biogas)	6	Thermal (3), power generation (1), unspecified (2)
Solar PV	8	Power generation (7), thermal (1)
Concentrated Solar Power	3	Power generation (2) and thermal (1)
Concentrated Solar Power, solar thermal and biomass (hybrid)	2	Power generation
Wind	1	Power generation
Wind and solar PV (hybrid)	1	Power generation
Bioenergy and hydropower	2	Power generation
Solid and liquid biofuel	1	Thermal
Electricity mix: fossil fuel, hydropower, biomass, wind, solar PV, solar thermal	1	Power generation
Fossil fuel and hydropower	1	Power generation

2.3.1.2 Solar

LCAs of solar energy technologies in the selected studies comprise solar PV technologies and concentrated solar power, which can be classed as either large or small scale, and either off-grid or on-grid. In the reviewed studies, off-grid systems are mostly used for power generation and thermal applications for different end-use sectors e.,g. PV mini-grids coupled with batteries or supplementary energy sources (e.g., Bilich et al., 2017), organic solar lamps (e.g., Espinosa et al., 2011), parabolic solar cookers (Andrianaivo and Ramasiarinoro, 2014), and combined heat and power systems (Banacloche et al., 2020) (Table A 2 in SI).

On-grid commercial and utility-scale PV and concentrated solar power systems are also analysed (e.g., Ito et al., 2016; Viebahn et al., 2011). In some instances, solar PV technologies are cross-compared to assess the impact of location on environmental performance without specifying the market served (e.g., Serrano-Luján., 2017). Yet, markets (i.e., on-grid and off-grid) determine the technical composition of the generation infrastructure and distribution grid, hence, have a direct bearing on the overall environmental impacts of solar PV systems at different locations. Of the 6.3 GW installed solar PV capacity in Africa in 2019, about 1GW was off-grid (IRENA, 2020). Additional solar PV capacity forecasted for Sub-Saharan Africa by 2025 is 1 GW off-grid to meet energy access targets and about 4 GW utility- and commercial-scale (IEA, 2020a). Considering the relative contribution of off-grid and on-grid solar PV to environmental impacts, the potential burden of the forecasts can be estimated to inform mitigation decisions on the continent to minimise unintended consequences such as high resource consumption and waste volumes.

LCAs of solar PV in the reviewed studies are mostly for ground-mounted systems. Comparatively, similar assessments conducted for high-income countries explore a broader range of installations i.e., roof-mounted, façade integrated, building integrated, and ground-mounted (Gerbinet et al., 2014). The environmental impacts of ground and roof installations are mainly associated with the length of the transmission and distribution infrastructure (i.e., cables and poles) and the amount of concrete and steel used in mounting structures (Kouloumpis et al., 2020).

Solar PV (ten studies including hybrid systems and energy mixes) is more common than concentrated solar power (three studies including hybrid systems) in the reviewed sample (Table 1). More research interest in solar PV can be attributed to the fact that its installed capacity (5,122 MW) was higher than that of concentrated solar power (975 MW) on the continent in 2018 (IRENA, 2019). There are more solar PV than concentrated solar power installations in Africa because of i) the ease of deploying solar PV on a small scale, ii) the need to access scarce water resources for concentrated solar power plants, and iii) the technological simplicity of solar PV compared to concentrated solar power. First-generation solar PV (crystalline silicon) is most researched in the reviewed studies due to its maturity and wide market share globally (specifically, it accounted for 95% of global solar PV production in 2019 (Fraunhofer ISE, 2020). LCAs for second-generation PV (e.g., cadmium telluride, copper indium diselenide) are scarce both in Africa (Table A 2 in SI) and in high-income countries (Gerbinet et al., 2014). Thin-film PV was produced at an industrial scale at an annual production volume of 7.5 GWp (around 5% of the market) in 2019 with a market share of 5.7 GWp cadmium telluride, 1.6 GWp copper indium gallium selenide, and 0.2 GWp amorphous silicon (Fraunhofer ISE, 2020), while third-generation PV technologies are still at the infancy stage. The installed capacity of second and third-generation solar panels in Africa is expected to increase in line with IEA's 2025 forecasts (IEA, 2020a). In the future, LCAs of these technologies adapted to the African conditions need to examine the end-of-life to underscore impacts associated with waste treatment preparedness and readiness for diverse solar PV technologies and potential problems such as leaching of toxic heavy metals like cadmium. As new solar PV technologies advance and become cost-competitive, so will their global market penetration and applications that go beyond power generation to include power-to-gas, power-to-heat, power-to-fuel, and related energy storage infrastructure.

2.3.1.3 Other renewable sources: wind, hydropower, and geothermal

Wind-related LCAs are scarce and mainly focus on small and large onshore wind turbines rated between 2 kW and 20 MW installed in South Africa (Andrae et al., 2012), Libya (Al-Behadili and El-Osta, 2015), and Nigeria (Gujba et al., 2010). It is not clear why wind has received less attention in the literature despite its significant contribution to Africa's renewable electricity generation: in 2019, the installed capacity of wind was 5.8 GW (12% of the continent's renewable generation) (IRENA, 2020). Africa has good offshore wind resource potential in a third of its coastal locations with Somalia, Madagascar, Mozambique, Morocco, and South Africa showing the highest energy yield potential (Elsner, 2019). The continent is harnessing its onshore wind potential and has not yet tapped into the offshore market, although plans are underway in countries like South Africa (Craig, 2020; Skopljak, 2020). Several LCAs of wind energy have been performed in various countries outside Africa (e.g., Mendecka and Lombardi, 2019; Price and Kendall, 2012; Radaal et al., 2014), focusing on onshore and offshore systems, horizontal and vertical axis wind turbines, and rated power.

LCA of hydropower is performed in four studies in the sample (Afrane and Ntiamoah, 2012; Brizmohun et al., 2015; Felix and Gheewala, 2012; Gujba et al., 2010) for small and large hydropower systems of between 561 MW and 5,748 MW. Hydropower has been the focus of LCAs in high-income countries such as the European alpine and non-alpine zones (e.g., Mahmud et al., 2018) and emerging economies such as Brazil, India, and Thailand (e.g., Asdrubali et al., 2015). Most of these LCAs are for in-country impacts of micro, small, and large impoundment, or diversion hydropower systems, with little emphasis on transboundary consequences (e.g., upstream and downstream water levels and discharge, sedimentation, and loss of aquatic species (Yu et al., 2019)). Like wind, LCAs of hydropower in Africa are few despite it being the largest source of renewable energy in Africa: it accounted for 74% of the continent's renewable energy generation compared to 52% of the global share (IRENA, 2020).

None of the reviewed studies performed LCAs of geothermal energy despite substantial installed capacity in Africa (around 830 MW in 2019 of which 99% is in Kenya (IRENA, 2020)) and resource potential of more than 15 GW in East Africa (Teklemariam, 2011). Worldwide, there are few LCAs of geothermal energy production even in leading producers like the USA, Japan, New Zealand, Germany, and Iceland (Bayer et al., 2013). LCA of geothermal energy has not received much attention in literature because associated environmental impacts are highly site-specific and recommendations for the sector cannot be deduced from individual studies (ibid).

2.3.2 The LCA process

This section presents significant methodological issues in the reviewed studies and discusses key findings that are specific to the LCA of renewable energy on the continent. Figure 1 summarises the methodological issues identified in the four stages of LCA as follows: (i) inadequate and omitted goal descriptions; (ii) undefined functional units and system boundaries; (iii) inadequately described and excluded inventories; and (iv) lack of justification for incompleteness in the coverage of impact categories, unstated impact assessment methods, and omission of uncertainty analyses. These issues create uncertainty in the LCA results and affect their reproducibility.

2.3.2.1 Goal definition

The number of studies with adequately defined goals is low: about 49% of the reviewed sample (Table A 2 in SI and Figure 1). Some studies that do not define the goals of the LCA use overarching aims or objectives to explain what the study is about (e.g., Lansche and Müller, 2017), while others describe scenarios (e.g., Galgani et al., 2014).

Lack of proper goal definition makes it difficult to determine the target audience and how the LCA results should be applied for subsequent monitoring and evaluation purposes against baseline conditions.

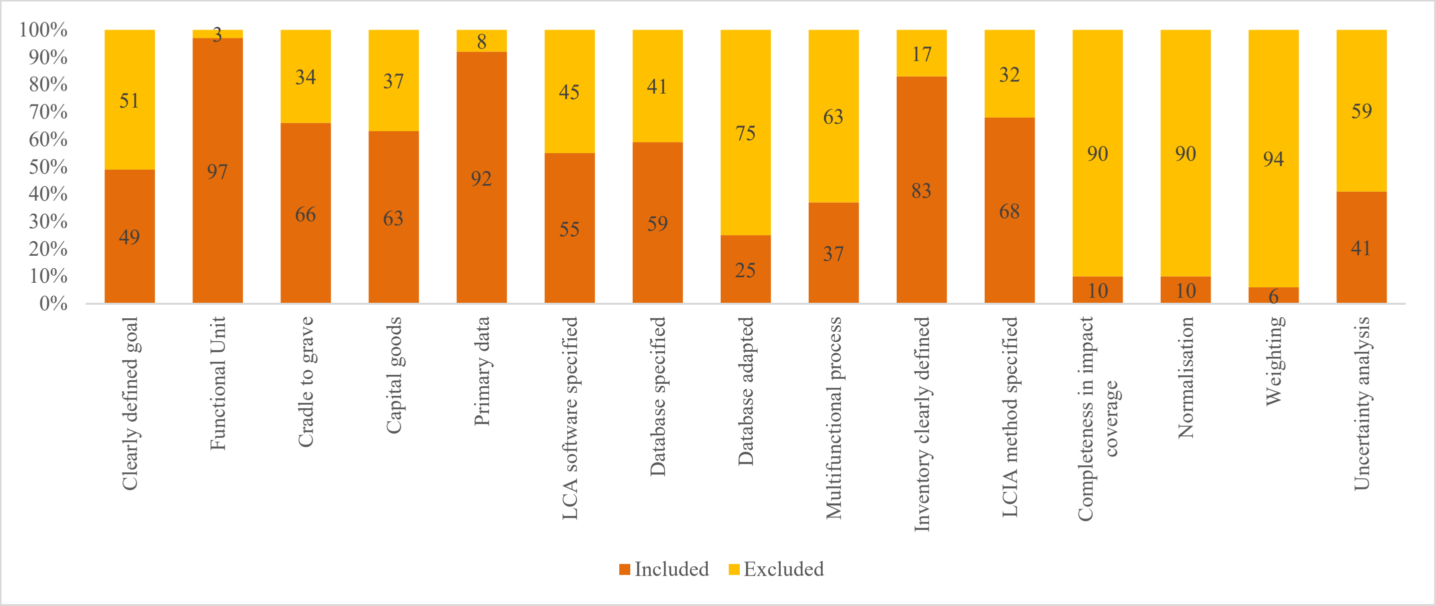


Figure 1: Significant methodological issues identified in the reviewed studies

Based on the assessment of the reviewed studies, their goals can be categorised as follows:

- Comparative studies of renewable and non-renewable energy technologies that deliver similar functions (24 studies (e.g., Vrech et al., 2018)). These studies identify products and processes that account for the highest environmental impacts to inform decision-making at the micro- and macro-levels;
- Non-comparative studies to support policy decisions at the meso- and macro-levels (one study (Gujba et al., 2010)) particularly regarding synergies and trade-offs, elimination and substitution;
- Non-comparative studies for monitoring and accounting purposes (17 studies (e.g., Okoko et al., 2017)) aimed at evaluating environmental impacts of decisions that have already been made;
- Hotspot identification, i.e., the contribution of parts or stages of a product to environmental impacts (one study (Mashoko et al., 2013)), and the improvement

potential such as technological or policy intervention (three studies (e.g., Ekeh et al., 2014));

- An assessment of environmental impacts alongside economic aspects (four studies (e.g., Ayodele et al., 2018; Banacloche et al., 2020);
- Assessment of social impacts of renewable energy development (one study (Mbohwa and Myaka, 2010); and
- Life cycle inventory compilations without environmental impact assessment (two studies (Brent et al., 2010; Chinongo et al., 2015)).

In addition to the main goal of performing LCA, about 29% of the studies have multiple goals beyond the evaluation of environmental impacts, which vary depending on the target audience and intended use of the results:

- Cost assessment of renewable energy development (seven studies e.g., Ito et al., 2016; Mahlangu and Thopil, 2018);
- Socioeconomic aspects (Banacloche et al., 2020; Herrera et al., 2020);
- Energy balance to determine the energy and carbon payback period of renewable energy projects (11 studies e.g., Achten et al., 2010; Ayodele et al., 2018);
- Optimal land allocation and value chain optimisation in biodiesel systems (Almeida et al., 2016);
- Inventory creation and comparison (Andrianaivo and Ramasiarinoro, 2014; Mashoko et al., 2013);
- Analysis of resource potential and projections of future electricity production (Felix and Gheewala, 2012); and
- Establishing emission factors (Njenga et al., 2014).

Life cycle sustainability assessment of supply chains gives evidence of environmental, cost, and social consequences of renewable energy that can inform the low-carbon transition at policy, industrial, and operational levels. However, it has not been extensively researched in studies set in Africa, with only seven including life cycle costing and four including social aspects. A holistic approach to LCA gives different outcomes across countries depending on socio-economic and environmental contexts. Therefore, LCAs should incorporate multi-criteria decision-making based on stakeholder consultations. For example, in Turkey, social, cost, and environmental trade-offs rank hydropower as the most suitable renewable energy option followed by geothermal and wind (Atilgan and Azapagic, 2016). Similarly, a UK-based study shows that renewable energy must be paired with nuclear to achieve long-term decarbonisation targets at lower costs and social risks (Stamford and Azapagic, 2014).

2.3.2.2 Scope definition

2.3.2.2.1 Functional unit

Functional units vary significantly in the reviewed studies (Table A 2 in SI), depending on the goal definitions, renewable energy technology type, and application. In this literature review, renewable energy systems are grouped based on their functions: power generation, transport, and heat generation, and further sub-grouped into technology types to allow comparison based on the functional units and implications on the LCA results. Three studies do not define functional units. The following functional units have been identified in the reviewed studies, grouped by sector:

- *Power generation technologies:* the functional units for electricity generation from wind, hydropower, PV, and concentrated solar power are power output (1 watt), energy yield (1 kWh, 1 MWh), and rated peak power output (1 kWp). The functional units for solid and liquid bioenergy and biogas are for energy yield (delivery of kWh, MWh, GWh), the energy content of the feedstock (MJ), energy consumed (kg, tonne, e.g., of biomass), land coverage (ha), and average annual waste generated (for waste-to-energy conversion). Energy mixes comprising hydropower and other renewable sources of energy use MWh as a functional unit.
- *Thermal/heat generating technologies:* the functional units are related to energy content delivered or consumed (MJ), the volume of energy produced (m^3), the quantity of fuel used (kg), net energy for cooking over time, and land coverage (ha).
- *Transport:* the functional units are related to the amount of fuel produced or consumed (tonne) or calorific value (MJ).

Functional units and reference flows serve as the basis for normalising and comparing LCAs of renewable energy systems that have the same function and determine how results are interpreted. As discussed by Bjørn et al. (2018a) and Laurent et al. (2013), functional units should include the function of the system; otherwise, it becomes a reference flow. Some reviewed studies describe the functional unit as a physical quantity, e.g., 1 MJ of heat or 1 kWh of electricity, but do not specify the function of the system. LCA results may lead to inaccurate conclusions should incorrect functional units be selected in such cases. Different functional units for a given renewable energy technology yield varying degrees of environmental impacts, hence, should be carefully selected depending on the functions of the systems and system boundary. For example, in the reviewed studies of liquid bioenergy for electricity generation, functional units based on physical characteristics (e.g.,1 kg of feedstock (e.g., Somorin et al. 2017)), the function of the system (e.g.,1 kWh of electricity generated (e.g., Almeida et al., 2016)), or energy content (e.g., 1 MJ (e.g., Onabanjo and Lorenzo (2015)) yield variable results that are not comparable. The use of physical quantities of a system (e.g., weight) as functional units rather than functional attributes may affect the interpretation of results (Panesar et al., 2017). In some cases, the selection of functional units may not be straightforward for multifunctional processes that have co-products (Ahlgren et al., 2015) e.g., electricity and heat produced by a hybrid solar PV-biomass system. The effects of these choices on LCA results are discussed in the impact assessment section 2.3.2.4.

2.3.2.2.2 System boundary

The system boundary specifies the life cycle stages, processes, resources, and emissions that are included in the studied system. Thirty-four studies have system boundaries spanning from cradle to grave as shown in Figure 1 (e.g., Okokoet al., 2017). Boundaries of three studies on transport are from well to wheel (Almeida et al., 2011; Fawzy and Romagnoli, 2016; Onabanjo and Lorenzo, 2015), and one study from cradle to cradle (Bilich et al., 2017). Among the rest, twelve studies have shorter system boundaries from cradle to gate (e.g., Ishimoto et al., 2018), and two studies on transport well to tank (Amouri et al., 2017; Vrech et al., 2018). Notably, 11% of the studies are not transparent in their system boundary definition, particularly regarding the inclusion or exclusion of specific aspects (e.g., capital goods) in the life cycle stages. This lack of transparency has implications for the robustness of the results.

Three important aspects stand out in the definition of system boundaries in the reviewed studies: the inclusion or exclusion of (i) end-of-life, (ii) land-use or land-use change, and (iii) capital goods. Limited or unavailable data or lack of consistency in the definition of these three aspects is a concern as it can affect the results of the studies and any recommendations based on such results.

2.3.2.2.2.1 End-of-life waste management

The end-of-life process is not comprehensively addressed in the reviewed studies (around 33% of them include this stage), even though the volume of waste is expected to increase substantially in Africa in line with the increasing installed capacity of renewable energy. Omission of the end-of-life from analyses can result in burden-shifting or misstating the actual impacts of a product.

Only seven bioenergy studies include the end-of-life processes such as digestate used as manure (Afrane and Ntiamoah, 2011; Nzila et al., 2012), bio waste recycled to briquettes (Njenga et al., 2014), waste converted to energy (Ayodele et al., 2017, 2018; Patrizi et al., 2020), and other waste from biorefineries (Brizmohun et al., 2015) in the system boundary, despite evidence of the potential influence in eutrophication, acidification, and climate change impacts (Rehl and Müller, 2011). The magnitude of end-of-life impacts of waste products from feedstock processing, transesterification, anaerobic digestion, or combustion varies depending on several factors (e.g., nature of the feedstock, treatment process, or final applications of stabilised waste). African-based LCAs that include all these factors are important because feedstock waste is mostly treated locally and results can be affected by local conditions.

System boundaries for wind and solar energy technologies mostly span the full life cycle with landfilling (54% of the studies on wind and solar) being the dominant end-of-life process (Table A 2 in SI). Recycling is the least covered in the reviewed studies (two out of 16 studies on wind and solar) because of the absence of representative data and whole-product recycling processes in existing databases. An area of concern in LCA studies is the uncertainty of results arising from the transparency and variability in modelling post-gate life cycle stages such as the end-of-life (Bhandari et al., 2015). Progress in LCA of solar PV recycling has been made to evaluate the environmental performance of different recycling processes. For example, comprehensive LCAs of recycling solar PV panels have been conducted in Italy (Latunussa et al., 2016), Thailand (Faircloth et al., 2019), and Belgium (Held, 2012; IEA PVPS, 2018). Similarly, analyses have been conducted for processing wind turbine waste in Germany and Ireland (Nagle et al., 2020).

As illustrated in Table A 2 in SI, off-grid solar PV systems are coupled with either lead-acid or lithium-ion batteries; however, none of the reviewed studies includes the impacts associated with the recycling of these batteries. Decentralisation of electricity markets by coupling variable renewable energy generation with storage is increasingly a part of the green energy transition globally (Brisbois et al., 2020) and calls for insights into the environmental impacts of battery recycling. So far, studies like Nordelöf et al. (2019) synthesise studies to describe the modelling approach of recycling lithium-ion batteries from around the world. Similar analyses centered on modelling the end-of-life of key battery technologies in Africa are crucial particularly with the proliferation of off-grid renewable energy technologies in the transport, heat, and electricity sectors. Specific conditions of battery recycling in Africa imply the need to develop locally adapted solutions, accounting for a significant role of the informal sector, local collection networks exporting lithium-ion and lithium ferrophosphate batteries to Belgium for processing (e.g., in Kenya and Nigeria (CLASP, UKAID, USAID, GOGLA, 2019; Closing the Loop, Fairphone, and Call2Recycle, 2020), and lead toxicity from formal lead-acid battery recyclers in countries like Tunisia and Mozambique (Gottesfeld et al., 2018).

2.3.2.2.2.2 Land-use and land-use change

Local impacts such as land-use and land-use change are critical for the production of energy crops globally due to food security and land ownership structure. From an environmental perspective, land-use change is largely associated with altering carbon pools and carbon stocks in soil and biomass (Hjuler and Hansen, 2018). The direct and indirect impacts of land-use and land-use change can be significant in biofuel production depending on the initial use of land, be it the conversion of cropland, fallow land, or forests. Only seven out of 28 studies on liquid and solid biofuels (excluding energy mixes and hybrid systems) include land-use and land-use change in their system boundary despite its importance for the greenhouse gas emission balance from the conversion of cropland or fallow land for energy crop production (Majer et al., 2009).

The omission of land-use and land-use change is not explained in most of the reviewed studies, and it is unclear if the resulting impacts are negligible. Uncertainties due to lack of site-specific data are given as a reason for its exclusion by Onabanjo and Lorenzo (2015). Therefore, the role of land-use and land-use change in potentially significant local impacts such as loss of ecosystem functions and global impacts such as climate change is not accounted for in most of the reviewed studies. Land-use impacts of even the well-established first and second-generation energy crops on the continent are not extensively documented and fully addressed, considering the sensitivity of ecosystems to localised impacts. Therefore, there is a need to develop more local LCAs to address these issues.

2.3.2.2.2.3 Capital goods

Capital goods are among the key drivers of environmental impacts for renewable energy, in contrast with fossil-fuel-based plants. For the latter, impacts of manufacturing the infrastructure are small in relative terms compared to impacts during the fossil-fuel use stage (Laurent et al., 2018). However, their inclusion or exclusion in the analysis is an area of contention in the LCA studies, depending on their relative contribution compared to other hotspots. In LCAs covering renewable energy systems, capital goods are relevant for climate change and toxicity impact categories (Frischknecht et al. 2007a). In agriculture-based LCAs (including energy crop cultivation), farm emissions are dominant sources of environmental impacts in most categories, except non-renewable energy demand where capital goods are significant (Aberilla et al., 2019).

Capital goods in the reviewed studies include farm machinery, power plants, solar panels, wind turbines, biogas digesters, and equipment for feedstock processing. In the bioenergy studies, the system boundary covers feedstock cultivation, processing, conversion, and use, with several cases (17 out of 39 studies including hybrid systems and energy mixes) accounting for impacts of farm inputs and infrastructure (e.g., Nzila et al., 2012). Feedstock in the reviewed studies is sourced and produced locally, hence the reason for its inclusion in system boundaries. Moreover, feedstock production contributes significantly to local, regional, and global impacts e.g., land-use change, pollution of ecosystems, ecotoxicity, and greenhouse gas emissions. Capital goods for power generation from bagasse are excluded in three studies (Brizmohun et al. 2015; Mashoko et al. 2013; Ramjeawon 2008), because the main function of the plant is to produce sugar, whereas electricity is only a co-product (Brizmohun et al., 2015).

Hydropower plants generally have low environmental impacts in their operation phase and high impacts in their construction phase (Frischknecht et al., 2007a). As such, the construction of hydropower plants is included in all system boundaries except one (i.e., Afrane and Ntiamoah (2012)), as dams constructed decades ago have a negligible impact on the present environment. Similarly, all reviewed studies on large-scale solid biofuel plants, solar PV, concentrated solar power, and wind farms include infrastructure in their system boundaries.

2.3.2.3 Life Cycle Inventory

2.3.2.3.1 Foreground and background data

Foreground data have high specificity when obtained through direct measurements, interviews, or questionnaires and lower specificity when sourced from secondary sources such as other LCA studies, national statistics, and industry reports (Bjørn et al., 2018b). Background data and processes, on the other hand, are mostly sourced from life cycle inventory databases, which contain average industry data specific to a given country, or region, or can be global datasets.

Three of the reviewed studies only use foreground data, 16 only secondary sources or background data, and 34 a combination of both (Table A 2 in SI). The use of secondary data may affect the accuracy of LCA results because these sources may not be an actual representation of the current conditions of a given context (EU-JRC-IES, 2010). Moreover, the reliability of results is affected by using secondary data for key inputs such as feedstock in anaerobic digestion, because biomass cultivation and yield depend on where and when it is grown and collected (Bacenetti et al., 2016). The limitations of using secondary data alongside primary data in LCA.

The Ecoinvent database (Wernet et al., 2016) is the main source of background data in the reviewed literature sample (39% of the studies used it exclusively). Ecoinvent is also used in combination with other databases such as Gabi (thinkstep AG, 2013) (five studies), Agri-footprint (Blonk Consultants, 2014) (three studies), Idemat (Delft University of Technology, 2015) (one study), US life cycle inventory (NREL, 2012) (one study), BUWAL 250 (BUWAL 250, 1996) (one study), and ETH-ESU 96 libraries (ESU, 1996) one study. Two studies exclusively use free databases but do not name them, while one study uses GEMIS (IINAS, 2001). About 37% of the studies do not specify the databases used. A detailed explanation of the representativeness of data in the reviewed studies is discussed in section 2.3.2.3.2 .

Regarding the LCA software, 43% of the studies use SimaPro (PréSustainability, 2016), while 9% use GaBi (thinkstep AG, 2013), one study (Gujba et al., 2010) combines both GEMIS and SimaPro while Carvalho et al. (2019) use SimaPro with LEAP. Around 22% of the studies use equations to compute LCAs manually. LCA software makes it possible to model complex or large inventories and present the results for several impact categories, which is not always easily achieved with manual computation using equations. The number of impact categories that can be considered with manual computation is low, for example, about 71% of the articles that used equations in place of software calculated one impact category, and 29% calculated up to three impact categories. Open-access software such as OpenLCA (OpenLCA, 2018) makes it possible for LCA practitioners to reduce the uncertainties in their calculations where commercial software is unaffordable. However, it is not utilised in the reviewed studies. Studies that use free databases do not specify if free software was used in the modelling process.

The reproducibility of LCA studies depends on the transparency of the inventory. About 82% of the reviewed studies describe their inventory and the sources of material inputs and processes, while nine studies have inadequately described inventories, making the reproducibility of the results difficult. All studies make assumptions (such as the type of transport vessel, the lifetime of systems, waste treatment scenarios, and handling multifunctional processes) to a varying degree of detail in the inventory.

2.3.2.3.2 Representativeness

According to the ILCD guidelines (EU-JRC-IES, 2010), the quality of life cycle inventory is determined by its (i) representativeness in terms of time, technology, or geographical location; (ii) completeness in terms of covering impact categories in the inventory; (iii) precision; and (iv) appropriateness of the methodology. In this section, the representativeness is assessed to determine the quality of data of the reviewed studies. The aim is to determine how the inventory data in the reviewed studies reflect the actual conditions of the systems under study.

2.3.2.3.2.1 Time representativeness

Time representativeness refers to the actual time when the data are collected, rather than the year of publication of a secondary source or the year when a unit process is modelled (EU-JRC-IES, 2010). Ideally, inventories for scenarios for the past, present, or future need to be modelled using data that accurately represents time in each case. The year of inventoried data from primary and secondary sources is not given in most studies. Additionally, some studies (e.g., Pradhan and Mbohwa, 2017) acknowledge the use of outdated data in the inventory due to the unavailability and incompleteness of up-to-date information. The results and recommendations of such studies should, therefore, be interpreted and applied with caution. For example, data on the cultivation of energy crops for biofuel production is time-sensitive because crop yield varies with seasons, farming practices, and environmental changes over the years. Similarly, renewable energy technologies are continually undergoing research and development to optimise their performance and resource efficiency. Technological advances in well-established and newer generations of renewable energy have a direct effect on the resource and emission flows, and, therefore, data and bills of materials used in the inventory should be representative of such temporal aspects to minimise the use of outdated data.

2.3.2.3.2.2 Geographical representativeness

Geographic representativeness determines how well the inventory data represents a system or process in relation to the site, region, or country (EU-JRC-IES, 2010). In the reviewed studies, data on emissions, materials, and energy flows obtained from secondary sources, or national averages are often used together with primary data without emphasis on local conditions or adapting them to study context.

A major concern when using generic databases to describe background processes is the geographical representation of data. Most of the studies (42%) are based on databases that were developed within the North American and European conditions and do not necessarily apply to the African context. For example, Ecoinvent is a European-developed database and lacks product unit processes or system processes adapted to most African conditions. Therefore, it is challenging to perform specific geographical coverage for in-country inputs such as electricity (Almeida et al., 2016). LCA databases are being developed for some African countries. For example, South Africa and Uganda have created roadmaps for the development of national LCA databases (Life Cycle Initiative, 2019; Sonnemann et al., 2018), while Tunisia and Morocco are at the early stages of database development (Life Cycle Initiative, 2018). However, many African countries are yet to start the development of national LCA databases, thus necessitating the use of datasets from other regions. Particularly for renewable energy, the version of Ecoinvent 3.6, included for the first time datasets for technologies such as solar PV for Tanzania and South Africa and wind for South Africa (Ecoinvent, 2019) but its coverage of the continent's renewable energy technologies is still low. Studies of LCA of renewable energy in Africa, thus, still rely on global datasets or datasets from other regions.

Thirteen studies (e.g., Almeida et al., 2016; Brent et al., 2010) adapt processes in the databases to local conditions. Adapting databases includes using the actual capacity of systems, efficiencies of machines, operating hours of power plants, energy consumption, and material processing. In two of the studies, not all relevant local inventory for components is available, and hence, data are adapted from different studies or countries that have similar system processes. For example, Amouri et al. (2017) obtained primary data on farm inputs from the literature of other low-income countries and adapted it to the agricultural conditions in Algeria.

The level of uncertainty in LCA results is high when databases and secondary data are not adapted to local contexts. For example, Galgani et al. (2014) attribute the uncertainty in their study to the use of non-local data for Ghana's transport emissions and emissions from anaerobic digestion. In biofuel production, uncertainties stem from the use of generic data for biodiesel production (Somorin et al., 2017), harvests and changing growing seasons, and logistics in the value chain (e.g., distance from farm to oil processing facilities) (Brent et al., 2010).

2.3.2.3.2 Multifunctional processes

Multifunctional processes are those that offer more than one function and deliver co-products or more than one service (Bjørn et al., 2018a). The ISO 14040 standards (ISO 2006a), in their hierarchy of solutions for dealing with multifunctionality, recommend system boundary expansion before resorting to allocation.

Seven studies for liquid biofuel (e.g., Achten et al., 2010; Fawzy and Romagnoli, 2016) and biogas production (Lansche and Müller, 2017) perform system boundary expansion. When performing system boundary expansion, the main system is compared to a reference system that relies on fossil fuels, and substitution is done in the reference system to avoid the production of functional equivalents. For example, biogas production in the main system prevents the production of natural gas in the reference system. Twelve studies (e.g., Amouri et al., 2017; Mashoko et al., 2013) solve multifunctionality by allocation (i.e., inputs and outputs are divided among the co-products or the functions). For example, environmental impacts for biogas production are attributed to livestock keeping (Okoko et al., 2017) and the use of digestate as fertiliser (Afrane and Ntiamoah, 2011). Allocation for liquid biofuel is based either on energy content (e.g., Amouri et al., 2017; Eshton et al., 2013) or mass content (e.g., Onabanjo and Lorenzo, 2015).

Given that system boundary expansion is not feasible for power generation from bagasse, as the co-products of the sugarcane production process (i.e., bagasse and molasses) cannot be produced by a reference system, allocation is based on economic value (e.g., Mashoko et al., 2013; Ramjeawon, 2008). Economic allocation is done according to the market value of the co-products, where by-products with low commercial value are allocated low shares of environmental impacts (Bjørn et al., 2018a). For example, molasses is allocated the smallest percentage (2%), followed by electricity production from bagasse (18%), followed by sugar (8%) (Mashoko et al., 2013).

Multifunctional processes affect LCA results depending on the type of co-products that a system yields, associated flows of resources and wastes, and the method used to handle multifunctionality. Therefore, the comparison of the impacts across the reviewed studies is limited to products that undergo the same multifunctional process. Notably, the approach to the handling of multifunctional processes differs across the studies of the same renewable energy source e.g., bioenergy, and it might be confusing to decide which process to use for specific applications. The hierarchy recommended by ISO 14040 (2006a), whereby system boundary expansion should be prioritised over allocation, is not always adhered to in LCA studies. For example, co-products of liquid biofuels are similar, yet six of the reviewed studies apply system expansion (e.g., Almeida et al., 2015), whereas four of the studies use allocation (e.g., Somorin et al., 2017).

System boundary expansion, substitution, and allocation affect policies on emission reduction and the use of co-products. For example, the substitution method is mandated by low carbon and renewable energy standards in the USA; substitution and economic allocation is mandated by the renewable transport fuel obligation in the UK; and substitution and energy content allocation is mandated by the European Union’s renewable energy directive (Wardenaar et al., 2012). The impact of LCA depends on the multifunctional process adopted in the directive (ibid). Few emerging economies in Asia, South America, and Africa (e.g., China, Thailand, Brazil, Colombia, and South Africa) have energy policies that incorporate LCA and life cycle thinking (Sonnemann et al., 2018) although it is unclear whether multifunctionality is used as a decision making factor.

2.3.2.4 Life Cycle Impact Assessment

Life cycle impacts can be classified as affecting human health, the natural environment, or natural resources and assessed at the midpoint level along the cause-effect chain or the end of the chain (Brilhuis-Meijer, 2014; EU-JRC-IES, 2010). Impacts are further classified as global where their effect is the same irrespective of where they occur (e.g., climate change), regional (e.g., eutrophication), or local (e.g., land-use change) (Gallego et al., 2010).

Figure 2 illustrates the impact categories considered across the reviewed studies. All studies but three (i.e., Brent et al., 2010; Chinongo and Mbohwa, 2015; Mbohwa and Myaka, 2010) analyse the climate change potential, while there is variation in the number of other impact categories. A similar trend is observed in LCAs of renewable power systems in high-income countries (Asdrubali et al., 2015). The large number of studies on climate change is associated with widespread political targets on climate change mitigation (UNFCCC, 2015). However, considering only this impact category does not reflect the overall environmental performance of renewable energy technologies, limits the usability of the LCA results, and may cause burden shifting.

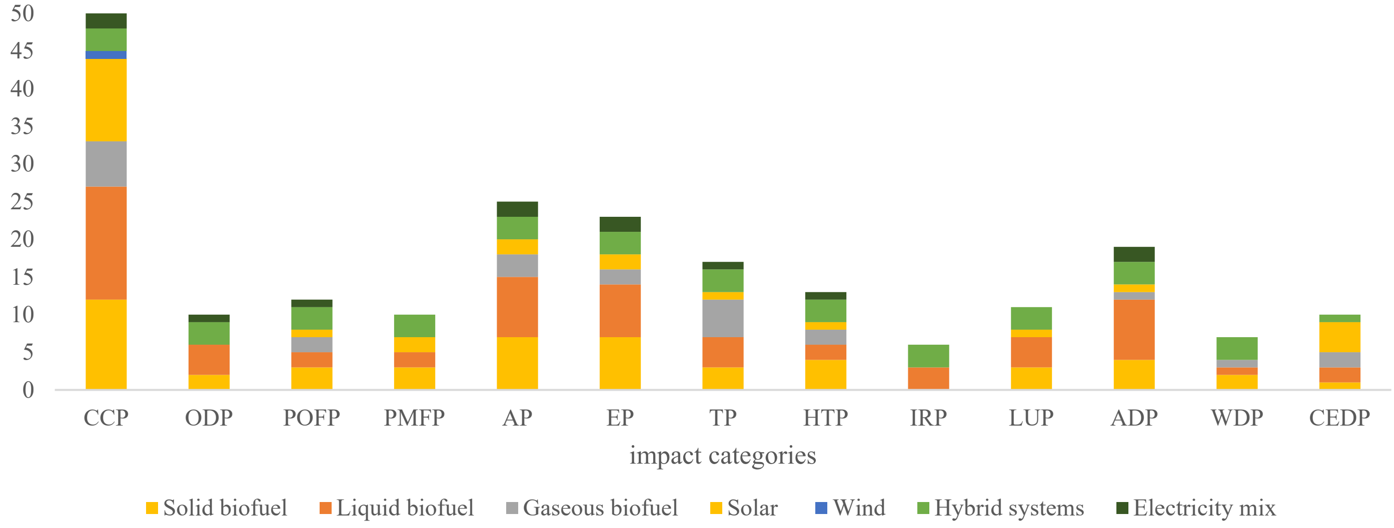


Figure 2: Frequency of impact categories in the reviewed studies. CCP – Climate Change Potential; ODP- Ozone Depletion Potential; POFP- Photochemical Oxidant Formation Potential; PMFP- Particulate Matter Formation Potential; AP- Acidification Potential; EP- Eutrophication Potential; TP- Toxicity Potential; HTP- Human Toxicity Potential; IRP- Ionizing Radiation Potential; LUP- Land Use Potential; ADP- Abiotic Depletion Potential; WDP- Water Depletion Potential; FDP- Fossil Depletion Potential; CEDP- Cumulative Energy Demand Potential

Other than climate change potential, acidification, eutrophication, abiotic resource depletion, and toxicity-related and cumulative energy demand are frequently studied in the reviewed studies (see Figure 2) due to the significance of these impacts. Cumulative energy demand is also well-covered in the literature of renewable power systems in high-income countries, followed by acidification and eutrophication potential (Asdrubali et al., 2015). About 18% of the studies (e.g., Andrae et al., 2012) perform complete assessments covering all impact categories; however, 22% (e.g., Ekeh et al., 2014) consider only climate change. The remaining studies (e.g., von Doderer and Kleynhans, 2014) perform partial impact assessments covering selected impact categories. Most of the studies that perform partial impact assessments (71%) do not give a justification for incomplete impact coverage and how it affects the interpretation of the results. Studies that do justify partial assessments (e.g., Carvalho et al., 2019) state that the selected impact categories are the most critical either to the goal of the LCAs or to the renewable energy technology being investigated. Regional impacts like acidification potential, eutrophication potential, and ecotoxicity are strongly dependent on local conditions (Gallego et al., 2011; Gallego et al., 2010) and should, therefore, be included in LCA studies of renewable energy in Africa.

Land-use change is a local impact that has high relevance to first-generation liquid and solid biofuel production in Africa. However, it is only assessed in seven of the 27 studies on liquid and solid biofuels (e.g., Achten et al., 2010) (excluding hybrid systems and energy mixes). Only seven studies (e.g., Hagman et al., 2013) assess the environmental impact of water use in biofuel production, despite its relevance to Sub-Saharan Africa, particularly the arid and semi-arid regions where biofuels like jatropha are grown (Kgathi et al., 2012). In particular, the production of energy crops in the regions of Africa with low annual rainfall, stresses river-based water reserves (ibid).

2.3.2.4.1 Impact assessment method

The Intergovernmental Panel on Climate Change greenhouse gas inventory and characterisation factors (IPCC, 2006; IPCC, 2007; IPCC, 2013) is the source most used to estimate greenhouse gas emissions (12 studies). Ten studies use CML method developed by Leiden University (Guinée et al., 2001), five studies use ReCiPe

(Goedkoop et al., 2009), and three use Impact 2002 + (Humbert et al., 2012). Other methods used include Eco-indicator 99 (Goedkoop and Spriensma, 2001), Cumulative Energy Demand (Frischknecht et al., 2007b), and Cumulative Exergy Extraction from Natural Resources (DeWulf et al., 2005). Some studies refer to the International Reference Life Cycle Data System guidelines (EU-JRC-IES, 2010), Nordic Guidelines on Life Cycle Assessment (Christiansen et al., 1995), and International Energy Agency Photovoltaic Power Systems Programme task 12 (IEA-PVPS, 2011). Most studies do not justify the choice of the impact assessment methods, making it difficult to determine the reason behind the popularity of some methods over others for LCA of renewable energy. Around a third of the studies do not mention the impact assessment method used, and this lack of transparency affects the reproducibility of results.

CML, Impact 2002 +, and ReCiPe impact methods are developed for the North American and European context, and their use can affect the results, particularly those that are region-and site-dependent (Gallego-Schmid and Tarpani, 2019). Several studies have created characterisation factors for regional and local impacts e.g., eutrophication, acidification, and ozone formation potential factors for the USA (Norris, 2008) and global land-use impact factors (Schmidt, 2008). Regional and local characterisation factors for low-income countries in Africa, Latin America, and parts of Asia are scarce; hence, most assessments are performed using factors already included in the impacts assessment methods i.e., global or those developed for European and North American contexts. The absence of characterisation factors or impact methodologies adapted to African conditions may create uncertainty in the characterised results, particularly for regional and local impacts, considering spatial variations in the sensitivity of ecosystems. The degree of uncertainty depends on the life cycle stage of given renewable energy sources, impact category (e.g., land and water use), and sensitivity of ecosystems to emitted compounds and exposure levels. Accordingly, most of the reviewed studies omit local impacts such as land-use from their analyses.

2.3.2.4.2 Climate Change Potential

2.3.2.4.2.1 Bioenergy

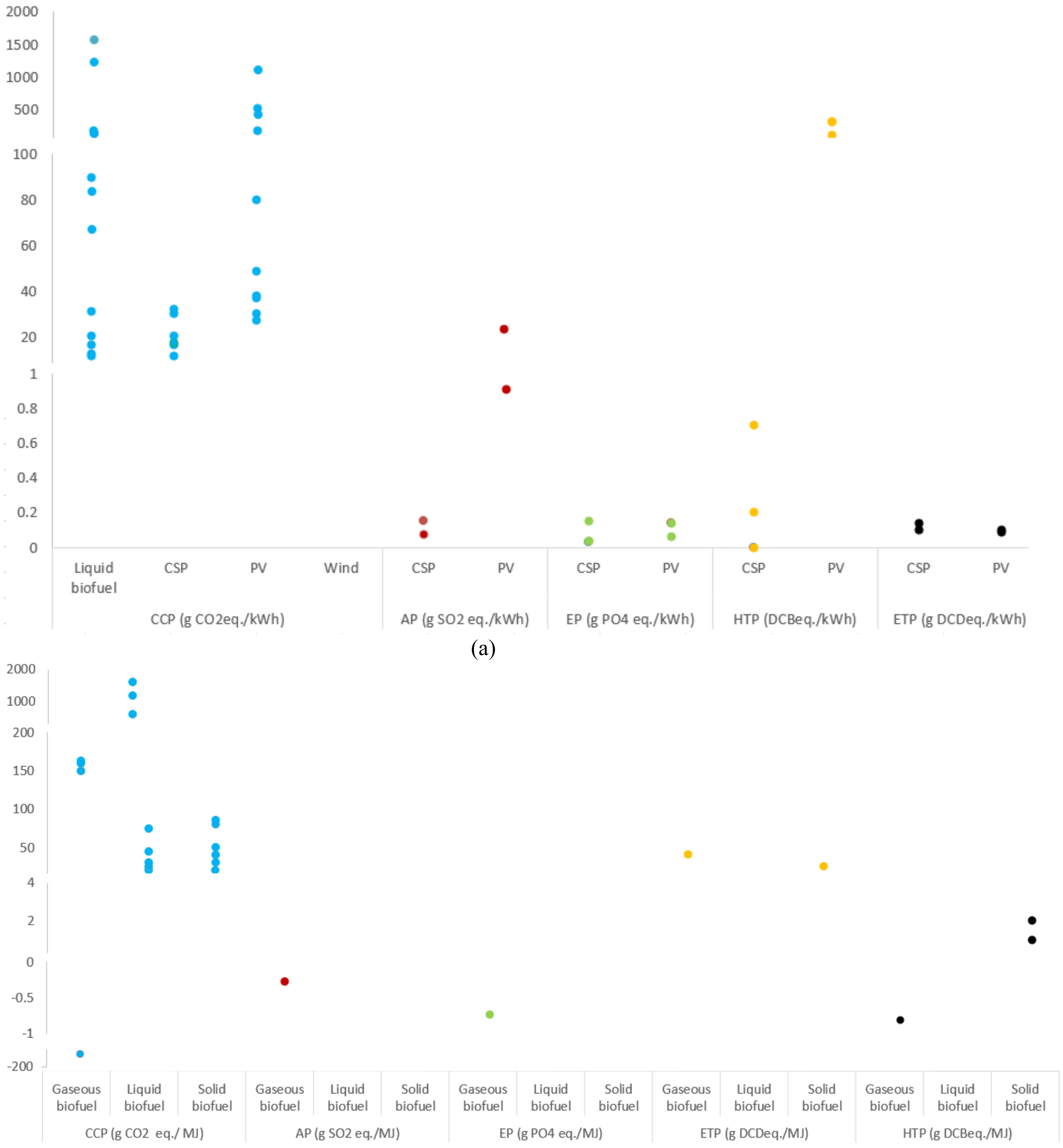
Variation in the climate change potential (CCP) of electricity, heat, and biodiesel generation from bioenergy sources results from differences in inventoried agricultural practices, functional units, and handling multifunctional processes. Figure 3 shows the range of CCP of bioenergy for electricity and heat generation. CCP range for renewable transport is excluded because of the low number of studies in the sample and the use of different functional units that are not comparable to each other. Bioenergy crops in Africa are obtained from outgrower schemes, plantations, and commercial and non-commercial farming models. Biogenic emissions from farming practices are important when accounting for CCP of first and second-generation biofuels, whose feedstock is plant biomass. ILCD guidelines state that temporary storage of carbon can be accounted for in the inventory but not included in impact calculation unless it is considered infinitely rather than in the short term (EU-JRC-IES, 2010). However, it is still debatable if the effect of temporary carbon storage and biogenic emissions contribute to CCP because CO_2 emission during harvesting of biomass is sequestrated when biomass regrows (Brandão et al., 2013).

Fewer than 10% of the reviewed studies on bioenergy account for biogenic emissions (e.g., Ekeh et al., 2014). In these studies, the impact of biogenic emissions on net CCP varies across geographical contexts because of factors such as land-use change, the duration of crop rotation, type of biomass feedstock, soil types, the spatial scale of farming, type of farming (intensive or extensive), and crop yield. Notably, biogenic accounting is performed when bioenergy crops are grown solely for feedstock (e.g., jatropha cultivation for seed oil). When feedstock is derived from co-products of other processes (e.g., bagasse), some studies (i.e., Mashoko et al., 2013; Ramjeawon, 2008) justify the exclusion of biogenic emissions in calculations on the premise that the CO_2 that is released is absorbed during photosynthesis and that all carbon stock in sugar is recycled.

There are mixed findings on what is the main contributor to CCP in the reviewed studies depending on the system boundaries, the inclusion of land-use change and capital goods, region of crop production, farming practices, and feedstock type. Some studies (e.g., Achten et al., 2010) attribute significant CCP to emissions during the cultivation stage because of land-use impacts, fertiliser application, and amount of yield, although it is contentious which of the three is the most damaging. Other studies (e.g., Eshton et al., 2013; Onabanjo and Lorenzo, 2015) find that CCP is highest during the use stage when biodiesel is combusted, thereby, negating sequestrated carbon. However, the impacts of land-use change, capital goods, and fertiliser production on CCP were not factored in the LCA modelling of Eshton et al. (2013) and Onabanjo and Lorenzo (2015). These variations highlight the need for more LCAs and harmonisation of results to better understand the interaction between land-use change, yield, and fertiliser application in different agro-climatic zones in relation to CCP for different functional units, feedstocks, and life cycle stages to inform trade-offs.

Considering land-use change, the CCP of converting cropland in Mali with ten rotations for jatropha cultivation is 66.7 g CO2 eq./kWh compared to 172.0 g CO_2 eq./kWh of fallow land conversion (Almeida et al., 2015). Similar results are obtained in other regions e.g., deforestation for rapeseed and soybeans production over 25 years with no-tillage in Europe and Brazil respectively, results in biodiesel performing worse than fossil diesel (Reijnders and Hui-jbregts, 2008). These findings are a result of the alteration of carbon pools and stocks in the soil that can be governed by directives to consider multiple criteria in converting land. The European Union has such directives in place i.e., Renewable Energy Directive and Carbon Quality Directive to mitigate impacts of converting land that has high carbon stock content or biodiversity cover (JRC and European Commission, 2016). Policy and regulatory recommendations can be instrumental in, for example, permitting bioenergy systems that make use of degraded land, supporting integrated feedstock and food farming systems to minimise land use risks, setting emission thresholds and credits for feedstock (Berndes et al., 2011).

In regards to crop yield, a low-yield less intensive jatropha plantation in Mali has a CCP of 112.5 g CO_2 eq./MJ which is 12% higher than a reference fossil-diesel system (Almeida et al., 2014). Comparatively, a high-yield more intensive jatropha plantation has CCP that is 21% lower than the fossil fuel system (ibid). These findings imply that yield affects CCP more than the use of fertilisers when the functional unit is energy output because high fertiliser application does not necessarily result in a high yield and depends on other factors like precipitation. Other studies (e.g., Somorin et al., 2017) show that higher jatropha yields indeed lower CCP per energy output while increased fertiliser application increases CCP by 20%.



(a)

(b)

Figure 3: Environmental impacts of (a) electricity and (b) heat generation from bioenergy sources, solar photovoltaic, concentrated solar power, and wind turbines in the reviewed studies. The impacts are expressed per kilowatt-hour of electricity generated and per megajoule of heat. CSP-Concentrated Solar Power; PV-photovoltaic; CCP- climate change potential; HTP-human toxicity potential; AP- acidification potential; EP-eutrophication potential; ETP-eutrophication potential; kWh- kilowatt-hour; MJ- megajoule.

Functional units and handling multifunctional processes also cause variation in the CCP for systems with similar functions and feedstock, thereby, affecting mitigation decisions. For example, the CCP of 1 MJ of jatropha biodiesel consumed in a gas turbine power plant with mass allocation for jatropha and glycerol co-products is 973.9kg CO_2 eq./MJ (Onabanjo and Lorenzo, 2015). In a different system, 1 kg of jatropha biodiesel used in a similar power plant with energy allocation for glycerol and jatropha is about 700.0 kg CO_2 eq./kg (Somorin et al., 2017). The variation is caused by the different amounts of fuel input to deliver the function, carbon content, and calorific value per MJ and kg of biodiesel as well as the amount of greenhouse gas emissions that are attributed to the allocation methods. Mass-based functional units are appropriate for the comparison of fuel used in various technologies because the amount of fuel input is the same and, therefore, easily adjustable (Matheys et al., 2007). Conversely, technologies have different energy consumption requirements and conversion efficiencies; hence, energy-based functional units may not be appropriate for comparisons (ibid). The system boundary should be considered in the selection of functional units and the interpretation section should clearly state to what extent the LCA results can influence policymaking considering the extent of the boundary. For example, a mass- or area-based functional unit is suitable for a cradle-to-gate bioenergy system whose main function is feedstock production (e.g., Amouri et al., 2017). Similarly, an energy-based functional unit may be ideal for a cradle-to-grave bioenergy system whose main function is electricity generation.

LCAs of biofuels for transport in the reviewed sample are scarce and have different functional units, including 1 MJ of palm oil in a car engine, 1 tonne of biodiesel from castor oil, and 1 tonne of jatropha combusted (Achten et al., 2010; Amouri et al., 2017; Eshton et al., 2013); therefore, comparisons may be inconclusive. CCP of biodiesel use in the transport sector largely depends on feedstock, in addition to upstream and downstream processes, e.g., 848.0 kg CO_2 eq./ t for jatropha biodiesel in Tanzania (Eshton et al., 2013) and 997.0 kg CO_2 eq./ t for castor oil in Algeria (Amouri et al., 2017). The low number of LCAs of biodiesel application in Africa's transport sector impede conclusive deductions of the sector's contribution to CCP; therefore, there is substantial scope for future research. Besides, a cross-comparison of the effect of functional units and system boundaries for electricity, heat, and transport on CCP (i.e., mass, land area, energy supplied or combusted, and distance travelled) can serve as a decision support tool for practitioners and policymakers.

2.3.2.4.2.2 Solar energy

The CCP for solar energy in the reviewed studies varies depending on the technology, country of origin, the irradiance at the location of installation, and the lifetime of technology (Aberilla et al., 2020; Gaete-Morales et al., 2018; Stamford and Azapagic, 2018), among other assumptions made in the inventory. Figure 3 shows the CCP of electricity generation from solar PV and concentrated solar power in the reviewed studies. Hybrid solar systems (i.e., those coupled with other electricity, heat, or storage technologies) tend to have higher CCP compared to nonhybrid systems because of higher cumulative embodied carbon in the additional technologies. For example, the CCP of an off-grid cadmium telluride solar PV mini-grid in Kenya coupled with a diesel generator and batteries is 164.0 g CO_2 eq./kWh (Bilich et al., 2017) compared to 27.4 CO_2 eq./kWh CCP of a grid-tied cadmium telluride system in Morocco (Ito et al., 2016). In terms of solar PV technology, the organic polymer solar cell has a higher CCP (420.0 g CO_2 eq./kWh) (Espinosa et al., 2011) than some hybrid systems because of its short lifetime, low efficiency, and low energy yield. Organic polymer solar cells appear in two studies (Espinosa et al., 2011; Serrano-Luján., 2017) compared to maturer technologies like silicon (six studies e.g., Ito et al., 2016; Todde et al., 2019), cadmium telluride (three studies i.e., Bilich et al., 2017; Ito et al., 2016; Serrano-Luján., 2017) and copper indium diselenide (one study i.e., Ito et al., 2016).

Seven studies (e.g., Banacloche et al., 2020; Ito et al., 2016) explicitly analyse CCP in relation to the country of manufacture. The production stage is a major hotspot in LCAs of solar energy systems, and the magnitude of its impact is strongly dependent on the energy mix of the country of manufacture, i.e., countries whose energy mix is predominantly fossil-based have high CCP (Gaete-Morales et al., 2019). Most of the solar PV modules in Africa are sourced from mainland China whose electricity mix has significant shares of coal at around 64% (IEA, 2020b). Mainland China is the leader in solar PV production, accounting for 66% of global production in 2019 (Fraunhofer ISE, 2020), although the Chinese production process has a higher CCP compared to Europe (Stamford and Azapagic, 2018; Yue et al., 2014). For example, the CCP of monocrystalline-silicon modules manufactured in China is 72.2 g CO_2 eq./kWh compared to 37.3 g CO_2 eq./kWh for European production (Yue et al., 2014).

The impact of transporting solar PV modules from the manufacturer to the installation site and later to the disposal site is mostly negligible compared to production and waste treatment processes, e.g., 0.5 t CO_2 eq./MW for transportation impact compared to 1,491 t CO_2 eq./MW for production and 37 t CO_2 eq./MW for waste treatment (Ito et al., 2016). Transport impacts vary depending on the means, vehicle's fuel conversion efficiency, and distances between the manufacturer and the installation site, and, later in the life cycle, the waste treatment facility.

The balance of systems, such as inverters, mounting structures, and wiring cables, is a critical part of LCA because their environmental impacts are not negligible (Gerbinet et al., 2014). Eight of the reviewed studies (e.g., Todde et al., 2019) include the balance of systems in their inventory. The magnitude of CCP varies depending on factors such as the size, composition, and lifetime of the balance of systems in a solar PV system. For example, a lithium-ion battery can contribute 58% to CCP when coupled with cadmium telluride (Bilich et al., 2017) compared to a 5% contribution of a lithium polymer battery coupled with organic polymer PV (Espinosa et al., 2011). Mounting structures contribute about 6% to CCP of multi-crystalline solar PV systems (Ito et al., 2016; Todde et al., 2019).

As illustrated in Table A 2 in SI, most LCAs calculate the impacts of disposing of solar PV and concentrated solar power technologies in landfills, with only two studies (Andrae et al., 2012; Todde et al., 2019) including the CCP of recycling in the cumulative life cycle impacts of solar PV systems. Therefore, it is difficult to tell what percentage comes from this stage. CCP of recycling solar PV systems in LCAs set in Europe and North America are few due to lack of data (e.g., Gerbinet et al., 2014) and this is the case for Africa as well. CCP of transportation to landfills, intermediate treatment, and landfilling has been calculated in six studies. On average, intermediate treatment and landfilling of a 1 GW multi-crystalline PV system in Morocco is 37.0 t CO_2 eq./ MW compared to 13.0 t CO_2 eq./ MW for a similar system in France (Ito et al., 2016). The differences arise from variations in end-of-life waste treatment processes in the two countries.

The production stage of solar energy technologies is the main hotspot of environmental impacts, followed by the end-of-life. Most production activities take place outside Africa where upstream impacts occur while downstream impacts of disposal and recycling are shifted to the continent. Regulations on extended producer responsibilities to close resource loops have been adopted by several African countries like Kenya, Nigeria, and South Africa (Ministry of Environment and Forestry, 2020; Ministry of Environment, Forestry and Fisheries, 2020; NESREA, 2014). Nigeria has also integrated life cycle analysis in its national electronic waste regulation to inform the end-of-life pathways (NESREA, 2011). LCAs of landfilling and recycling under such policy and regulatory scenarios compared to baseline conditions can monitor and evaluate the effectiveness of policy instruments in solving the impending renewable energy waste challenge. Besides, the informal sector is a major player in electronic waste recycling in most African countries like Ghana (Forti et al., 2020); therefore, an integrated LCA focusing on social and economic aspects of the policy interventions is timely. So far, thirteen countries in Africa (e.g., Côte D'Ivoire, Cameroon) have regulations on electronic waste in place, while a few countries (e.g., Rwanda, Namibia) have formal recycling facilities coinciding with informal recycling (ibid).

2.3.2.4.2.3 Wind and hydropower

In the reviewed studies, wind turbines alone have a CCP of 10.5 g CO_2 eq./kWh in Libya (Al-Behadili and El-Osta, 2015), compared to 400.0 g CO_2 eq./kWh of hybrid wind-PV in South Africa (Andrae et al., 2012). Even lower CCP of 4.6 g CO_2 eq./kWh is recorded for recycled wind turbines in Libya, due to the avoided use of virgin materials and incineration (Al-Behadili and El-Osta, 2015). The number of LCAs for wind power in Africa is few for comparison purposes, but harmonised LCAs of studies conducted in various locations globally show that large off-shore wind turbines have a higher CCP median value (9.9 g CO_2 eq./kWh) than a large onshore installation (9.7 g CO_2 eq./kWh) because of the complexity of constructing and operating the systems as well as setting up transmission infrastructure (Mendecka and Lombardi, 2019). In onshore applications in various locations globally outside Africa, micro and small wind turbines have the highest CCP ranging 72.0 to 560.0 g CO_2 eq./kWh while offshore applications, which always comprise large turbines, vary between 7.7 and 32.0 g CO_2 eq./kWh (ibid).

Impacts from hydropower are mainly attributed to the construction stage and CH_4 emission from submerged vegetation and flooded land (Felix and Gheewala, 2012). Emissions from hydropower are correlated with latitude. The tropics record higher emissions of CO_2 and CH_4 from soil and flooded vegetation unlike temperate regions (Barros et al., 2011). For example, the CCP for reservoir and river run-off hydropower is 8,600.0 g CO_2 eq./ MWh in tropical areas of Mauritius (Brizmohun et al., 2015) compared to 3.6 g CO_2 eq./kWh river run-off in higher latitudes of Switzerland (Flury and Frischknecht, 2012). In Tanzania, biogenic methane from reservoir hydropower is expected to increase from 22,202.0 t CO_2 eq. in the year 2000 to 151,074.0 t CO_2 eq. in 2030, compared to 507.0 t CO_2 eq. and 2,124.0 t CO_2 eq. from river run-off over the same period, as the country increases its reservoir generation according to its energy masterplan (Felix and Gheewala, 2012).

2.3.2.4.3 Water and soil pollution: eutrophication and acidification potential (EP and AP)

As illustrated in Figure 3, major differences in the type and magnitude of eutrophication and acidification hotspots of bioenergy systems in the reviewed studies arise from the extent of system boundaries. For example, a well-to-wheel assessment of jatropha biodiesel in Nigeria shows that jatropha oil use is the main hotspot for marine eutrophication, contributing 50% of EP (Onabanjo and Lorenzo, 2015). The hotspot for aquatic eutrophication in a well-to-tank assessment of castor oil biodiesel in Algeria is the cultivation phase, which contributes 98% of EP (Amouri et al., 2017). Regional sensitivity of ecosystems to nutrients and acidifying compounds as well as inventoried assumptions on the farming scale, agrochemical inputs per hectare, fertiliser surface run-off per hectare, and N_2O and NO_x emissions from the soil per N input, can result in significant variations in the EP and AP, and therefore, should be calculated considering African conditions when possible.

Other than feedstock, the performance of South African-based lignocellulosic biomass systems that generate thermal energy have been analysed, showing EP and AP range of 21 to 57 t PO_4 eq./year and 82 to 237 t SO_2 eq./year, respectively (von Doderer and Kleynhans, 2014). Multi-output conventional and lignocellulosic biorefineries that generate bioenergy, biomaterials, and biochemicals are mostly spread out in North America, Europe, and Brazil (Girio et al., 2017). An example of such a system that converts lignocellulosic switchgrass to heat, electricity, bioethanol, and phenols shows that the impacts of biorefineries are lower than the impacts of fossil diesel systems in all categories except EP and AP due to burning biomass and NH_3 from N fertiliser (Cherubini and Jungmeire, 2010). For example, 2.82 kt PO_4 eq./year and 1.23 kt SO_2 eq./year impacts of biorefinery compared to 0.17 PO_4 eq./year and 1.17 kt SO_2 eq./year of fossil systems (ibid). Fertiliser use is the main cause of AP and EP in bioenergy systems and its substitute or elimination can result in significant environmental benefits.

Only seven non-bioenergy studies (i.e., 41% of the total) consider EP and AP in their impact analysis. This low number highlights the incompleteness of existing literature because solar PV, wind turbines, and hydropower dams are major contributors to EP and AP, particularly from the discharge of phosphorus and sulfur compounds during production and end-of-life. Unlike production, which takes place outside the continent, most components of renewable energy technologies in Africa end up in landfills in the absence of take-back schemes and adequate recycling facilities. EP and AP of recycling are mainly from acid leaching, neutralisation, and electrolysis (Latunussa et al., 2016), whereas the impacts of landfilling are from leached compounds. EP and AP impacts (and potential environmental benefits) of recycling are relevant for Africa and will vary depending on efficiencies of the process and the regional sensitivity of ecosystems to emissions. The lack of studies does not allow to obtain specific data for Africa, but to give a sense of scale, in Italy, the emission of NO_x in a recycling facility of crystalline silicon PV produces marine EP and AP impacts of 1.09 kg N eq. and 2.68 mol H^+eq. per ton of PV waste, respectively (Latunussa et al., 2016).

2.3.2.4.4 Ecotoxicity and human toxicity

Twelve studies on bioenergy (i.e., 31% of the reviewed sample, including hybrid systems and energy mixes) analyse ecotoxicity (i.e., terrestrial, marine, and freshwater) (e.g., Onabanjo and Lorenzo, 2015) compared to eight studies on human toxicity (i.e., human carcinogenic and non-carcinogenic toxicity) (e.g., Brizmohun et al., 2015). As shown in Figure 3, ecotoxicity and human toxicity impacts of bioenergy in Africa are highly variable. Feedstock production is the main hotspot for ecotoxicity and human toxicity in bioenergy systems. These impacts are caused by emissions from mechanised and intensive farming, and chemical use in the oil conversion process (Amouri et al., 2017; Brizmohun et al., 2015; Onabanjo and Lorenzo, 2015). LCAs of bioenergy systems globally attribute high toxicity to N fertiliser use and burning biomass indicating worse performance than reference fossil fuel systems (Cherubini and StrØmman, 2011). The use of chemicals in oil conversion in a jatropha biofuel system in Nigeria contributes 80% to aquatic ecotoxicity potential because of the transesterification process (Onabanjo and Lorenzo, 2015). However, manual extraction of oil as a substitute for hexane can reduce terrestrial ecotoxicity potential by 30% as shown in an Egyptian case study (Fawzy and Romagnoli, 2016). Possible impacts of eliminating chemicals during the oil extraction process include a reduction in respiratory and non-carcinogenic impacts (ibid).

Ecotoxicity and human toxicity impact categories are mostly omitted in LCAs of solar, wind, and hydropower in the reviewed studies, despite the relevance of these impact categories especially for metals such as cadmium, lead, mercury, that are mostly used in the generation, transmission, and storage infrastructure. Cumulatively, only five non-bioenergy studies consider ecotoxicity and human toxicity (e.g., Herrera et al., 2020). The implications of this low coverage are insufficient data to draw from and obtain solid conclusions regarding the sensitivity of regional ecosystems to toxic metals at different exposure rates. The emission of toxic compounds, carcinogens, and non-carcinogens from tailings and spoils from the mining of raw materials and disposal of metals such as copper in landfills is responsible for the ecotoxicity and human toxicity potential of solar PV and wind turbines. The risk is greater in Africa in the absence of adequate and sufficient infrastructure for treating electronic waste, particularly in remote rural off-grid areas, where solar home systems and pico PV systems have infiltrated. Most electronic waste in rural areas end up in unsanitary landfills or dumping sites (Cross and Murray, 2018) where the leaching process and exposure levels are heightened. Modern well-engineered facilities like sanitary, residual waste, and inert material landfills can reduce the risk of leachate compared to unsanitary municipal solid waste landfills. The reviewed studies do not specify the type of landfills or whether the waste is sorted and channelled to dedicated facilities.

2.3.2.4.5 Land-use change

Land-use change affects above-ground and below-ground carbon pools (soil and biomass), soil carbon content, and the quality of ecosystems (Hjuler and Hansen, 2018). Land-use change is site-specific, and therefore, there are large uncertainties associated with it, and these could be why it is assessed in only nine studies on bioenergy (e.g., Amouri et al., 2017). The magnitude of the impact of land-use change depends on the initial use of land. For example, the transformation of agricultural land to palm oil plantation for biofuel production in Cameroon improves the structural and functional quality of ecosystems by 9.2±5% and 6±10% respectively (Achten et al., 2010). On the other hand, the conversion of forested land reduces ecosystems' structural and functional quality by 47±5% and 31.9±9%, respectively (ibid). Palm trees are perennial crops with good vegetation structure and high production of biomass, which improves the ecosystem quality. However, conversion of forested or fallow land to energy crop cultivation lowers the above- and below-ground carbon stock, resulting in negative impacts.

Land-use change also affects carbon balance, as carbon emissions due to land clearing are absorbed during biomass regrowth under a given set of assumptions (e.g., Amouri et al., 2017; Njenga et al., 2014). However, the studies omit the initial land-use, and therefore, there are uncertainties in carbon savings or emissions. Additionally, the use of generic carbon data due to the absence of site- and region-specific data increases uncertainties, because carbon stocks vary significantly, even for similar vegetation (IPCC, 2006).

The quantity of carbon stock in carbon pools is affected by land-use change. Conversion of grassland, which has a biomass content of 8.5 t C/ha to jatropha plantation in

Cameroon, results in soil carbon stock reduction of 0.09 t C/ha/year (Vrech et al., 2018). In Mali, soil carbon stock reduction from jatropha plantation is 1.2±0.5 t/ha/year, and it is estimated to range between 0.1 and 5.1 t/ha/year upon biomass clearing (Almeida et al., 2016). The difference in soil carbon stock for the same vegetation type results not only from the scale of a jatropha plantation (e.g., large scale in Mali) but also from different soil types and climates of the two countries. The absence of site-specific data on land-use is a major challenge for LCAs of biofuel in Africa and has resulted in some studies (e.g., Onabanjo and Lorenzo, 2015) opting to leave out this impact category in their analyses. Almeida et al. (2016) acknowledge that modelling soil organic content for jatropha plantations by extrapolating data from other plantations and sites due to data unavailability affects the reliability of results.

2.3.2.4.6 Resource depletion

Fossil, minerals, and water depletion potential are not sufficiently discussed in the reviewed sample, particularly for biorefineries, hydropower dams, and wind turbines, despite the relevance of these impact categories in sustaining clean energy transition in Africa. Eighteen studies (e.g., Felix and Gheewala, 2012) analyse scarcity of fossil fuels and metals, while seven quantify impacts on water (e.g., Bartlett et al., 2014). The metal depletion potential of renewable energy systems is affected by the type and size of installations (on-grid and off-grid) and end-of-life pathways, as larger infrastructural projects, battery storage requirements, and recycling rates have a direct bearing on the availability of metals. For example, a 1000 kW hybrid CSP-biomass gasifier system that is landfilled has a metal depletion potential of 414.0 g Sb eq./kWh (Banacloche et al., 2020), compared to 0.0005 g Sb eq./ kWh for a 4.2 kW solar thermal-biomass hybrid plant that is also landfilled (Herrera et al., 2020).

The impact of battery requirements on metal depletion in decentralised systems has not been discussed in the reviewed studies. Neither have potential savings of avoided production of virgin materials from recycling processes. A study on metal scarcity globally based on increased demand for renewable energy by 2050 found that centralised and decentralised battery storage needs will increase the depletion of lithium, cobalt, and nickel (Moreau et al., 2019). However, an increase in recycling rates does not necessarily reduce metal depletion potential because renewable energy products have long lifetimes, therefore, demand for rare earth metals does not match scrap supply or offset demand from incumbent industries (Habib and Wenzel, 2014; Moreau et al., 2019). Decentralisation targets of Africa's renewable energy sector will increase the consumption of metals, which necessitates comprehensive assessments of the implications of waste treatment scenarios and their techno-economic feasibility on metal depletion potential. Besides, energy access and grid defection on the continent is largely pegged on decentralised renewable energy systems fitted with storage batteries.

An integrated assessment of water footprint and LCA in bioenergy systems has received little attention in the reviewed studies, with only a few documented cases e.g., from Mozambique (Hagman et al., 2013). The water depletion potential of biodiesel in comparison with fossil fuels depends on the availability of blue and grey water (i.e., ground and surface water, and precipitation) and crop yield. For example, biodiesel from a jatropha plantation with low yields of less than 1.1 t/ha has a water footprint of 0.09 l/MJ compared to about 0.05 l/MJ footprint of fossil diesel, while higher yields of 4 t/ha decrease the biodiesel's footprint to 0.03 l/MJ (Hagman et al., 2013). Higher yields have lower water requirements for nursery irrigation and dilution of agrochemicals per megajoule of fuel compared with lower yields (ibid). Crop yield affects both CCP and water depletion potential and is, therefore, a significant factor to consider when devising mitigation strategies. The water depletion potential of bioenergy value chains is complex because of interconnected factors such as type of feedstock, geographical and site specificities, the scale of farming, withdrawal rate, and feedstock conversion processes (e.g., physical, biological, chemical) (UNEP et al., 2011). The bioenergy-water nexus is relevant for Africa because of concerns over water security and conflict over its use (Mancosu et al., 2015). So far, studies on the integrated water footprint and LCA approach are scarce and there is a gap for assessments that look at existing synergies and trade-offs from a life cycle standpoint.

2.3.2.4.7 Normalisation and weighting

Five studies (e.g., von Doderer and Kleynhans, 2014) are explicit about implementing normalisation, while three studies (e.g., Hagman et al., 2013) perform weighting (see Table A 2 in SI and Figure 1). These studies use the generic world factors from the respective impact assessment methods (e.g., CML 2001 (von Doderer and Kleynhans, 2014), Impact 2002 + (Amouri et al., 2017), ReCiPe 2008 (Bilich et al., 2017)) since normalisation and weighting factors for most African countries are yet to be developed (Gallego-Schmid and Tarpani, 2019). Uncertainties in normalised results are caused by the reviewed studies not entirely describing the basis of their normalisation factors regarding geographical coverage (i.e., global, regional, or national), the population within the geographical zone, and the production system with regards to both industrial activities and reference systems. The use of global normalisation references or extrapolations for low-income countries due to the lack of site-specific environmental flow data also introduces uncertainties (Laurent and Hauschild, 2015; Pizzol et al., 2017), particularly in relation to regional and local impacts. Plans are underway to develop national LCA databases for African countries like Uganda and South Africa (Life Cycle Initiative, 2019), and there is substantial scope to extend such roadmaps to create regionalised normalisation and weighting factors.

2.3.2.5 Interpretation

Critical issues in the reviewed studies, that may affect the reliability of the results, have been identified in the preceding sections and summarised in Figure 1. Only 17 studies from the sample perform sensitivity analysis to test the robustness of the results and how they are affected by variation of different parameters. The sensitivity analyses in the liquid biofuels studies mostly explore how the impacts respond to varying yield levels, farm inputs, irrigation practices, use of fossil diesel, and cultivation land size (eight studies e.g., Vrech et al., 2018). For solar PV and concentrated solar power, the sensitivity analyses are related to the system performance, including optimistic and realistic scenarios on energy yield, energy and carbon payback times, and the effect of battery use and replacement in off-grid solar PV systems (five studies e.g., Ito et al., 2016). Other sensitivity analyses are performed to test how characterised results change with energy recovery, weighting, carbon price, and charcoal production (four studies).

Six studies perform uncertainty analyses (e.g., Achten et al., 2010) of which two use Monte Carlo analysis (Achten et al., 2010; Ekeh et al., 2014), while four mention that uncertainty analysis is done without being specific of the method used (e.g., Galgani et al., 2014). Nevertheless, some of these studies give uncertainty ranges of 'low and high' (Andrae et al., 2012; Galgani et al., 2014) or 'best case and worst case' (Lansche and Müller, 2017) for the assessed impact categories. Outcomes of sensitivity and uncertainty analysis are important because they can affect the recommendations to decision-makers regarding a given renewable energy source or technology.

2.4 Conclusions, research gaps, and recommendations for future research

This literature review has analysed LCA studies of renewable energy in Africa to critically evaluate advances in the sector, factors exacerbating environmental impacts, potential challenges associated with the forecasted growth of the sector, and mitigation options. Table A 3 in SI summarises the main issues and research gaps identified in the reviewed studies, their implications, and recommendations for future research. The number of LCA studies for Africa is still low as only 53 studies were found to meet the inclusion criteria. There is an unbalanced representation of each renewable energy source in the literature compared to installed capacity on the continent. For example, hydropower is the leading source in terms of installed capacity, yet its LCA is only covered in three of the 53 studies. Similarly, onshore wind energy is the focus of just two studies despite being the third-largest energy source on the continent.

First- and second-generation bioenergy is the most studied (72% of the studies including hybrid systems and energy mixes), yet the contribution of modern bioenergy (excluding traditional biomass) to Africa's energy mix is still low (3.5%). The application of solar technologies in off-grid and on-grid markets has received considerable attention in the literature, although LCAs of storage batteries are scarce despite their relevance to the attainment of electricity access targets on the continent. The transport sector has also not been extensively researched to be able to draw solid conclusions on mitigation pathways for biofuels and electric mobility with storage batteries. None of the studies performed LCA of geothermal power, third-generation and advanced biofuels, off-shore wind, while studies on thin-film PV, other than Cadmium Telluride, are scarce. As Africa's renewable energy grows in installed capacity and breadth of technology deployed, these gaps in energy source and technology coverage can limit the effectiveness of the continent's mitigation strategies due to unawareness of the extent of damage and scarce or unavailable data. Future studies should explore a full range of all power generation technologies deployed on the continent (i.e., geothermal power, onshore and offshore wind power, and hydropower), renewable transport (electric vehicles and biofuels), renewable heat, new generations of renewable energy technologies, and battery storage (lead-acid and lithium-ion batteries).

Methodological issues such as undefined goals and functional units, the non-transparent definition of system boundaries and inventories, choice of multifunctional processes, and incompleteness in coverage of impact categories affect the quality of results, interpretations, potential conclusions, and applicability. An assessment of the effect of pairing functional units such as mass, energy, land area, and volume with system boundary expansion, allocation, and substitution for renewable energy systems with similar functions can lead to different interpretations during decision-making, depending on the intended use of the results. For example, the European Commission's Renewable Energy Directive on bioenergy acknowledges savings of greenhouse gas emission calculated per unit of displaced fossil fuel paired with substitution of by-products. Functional units should be clearly defined and carefully selected because they determine why studies are conducted and how LCA results are interpreted. Future studies should investigate the effect of different functional units and multifunctional processes of the same technology and identify their suitability for various applications (e.g., heat, electricity generation, transport) and decision-making contexts.

So far, there are no LCA databases or characterisation, normalisation, and weighting factors exclusively developed for the African context; therefore, most studies rely on global averages from databases developed for North American and European conditions. Lack of temporal and geographical representativeness of data is, therefore, a challenge in the reviewed studies. Future studies should consider the time and geographical representativeness of data by adapting generic databases to study contexts. Where commercial software and database are unavailable, studies can use open source software, e.g., Open LCA. Another issue is the exclusion of end-of-life in most studies for reasons such as non-representative data. Yet, significant end-of-life impacts including toxicity, pollution, and depletion of valuable metals are imminent threats in Africa that necessitate further investigations of the continent's readiness and preparedness to integrate closed-loop circular economy strategies that handle bulk waste following the growth of the renewable energy sector. There is a need for dedicated studies on the end-of-life for all renewable energy technologies to assess Africa's preparedness and readiness to address potential issues of reusing, recycling, landfilling, and incinerating.

Climate change has been extensively researched in the reviewed studies because of the decarbonisation policy priorities of most governments in comparison with other impact categories. Non-climate change impact categories are also relevant for renewable energy, and their omission can result in burdenshifting, particularly for regional and local impacts such as eutrophication, ecotoxicity, and land-use that are affected by the sensitivity of ecosystems. Besides, incompleteness in coverage of impact categories provides insufficient and inconclusive evidence to support mitigation decisions without causing unintended rebound effects. The low number of non-climate change impact categories for heat, electricity, and transport hinder conclusive deductions of the overall burden of renewables in Africa, and this gap could be addressed in future studies to avoid burden shifting. There is also a need for decision-makers and future studies to explore national and regional characterisation, normalisation, and weighting factors specific to Africa which should be integrated into commercial and open-source LCA software.

Integrated LCAs of social, economic, and environmental aspects combined with multi-criteria assessments are crucial to informing synergies and trade-offs that cost-efficiently minimise environmental and social impacts of renewable energy in Africa. So far, only environmental impacts are extensively researched in literature with few studies combining life cycle costs with LCA while one study exclusively explores social aspects. Integrated LCA is a potential area of research for future studies that will support better decision-making to understand the feasibility and consequences of mitigation measures and limit unintended social and economic outcomes. Interpretation of LCA results also determines the outcomes and effectiveness of decision-making in policy and business. However, about 68% and 88% of the reviewed studies do not perform sensitivity and uncertainty analyses respectively, therefore raising concerns about the robustness and uncertainty of most LCA results of renewable energy in Africa.

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Chapter 3

Paper 2: A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value?

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This paper performs a systematic literature review of renewable energy business models in Africa. Sections, figures, and tables have been renumbered to comply with the structure of this thesis. The doctoral researcher (Velma Mukoro) is the lead author of this paper. Her contributions to the paper are the conception of the study, providing ideas, acquiring and processing data, analysis, interpretation, writing, and revising the paper. The co-authors' (Dr Maria Sharmina and Alejandro-Gallego-Schmid who are the lead author's supervisors) contributions are the conception of the study, critical revisions of the paper, and editing the final version for publication.

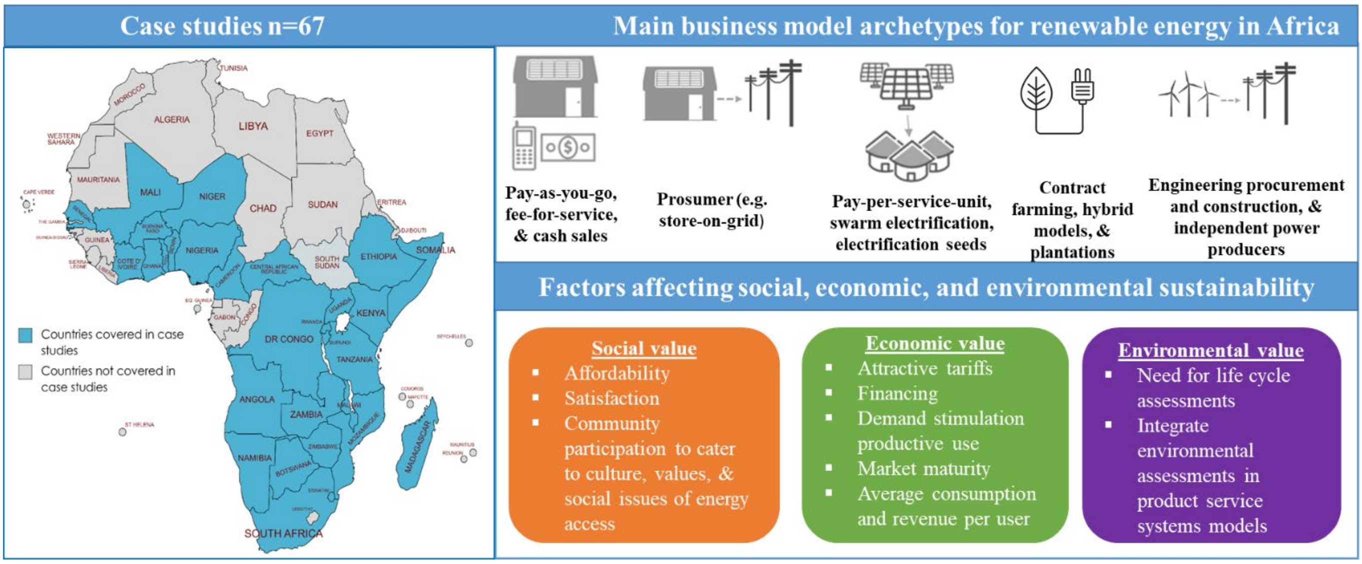
Abstract

Africa has the potential to base a significant proportion of its development on renewable energy. Business models will be instrumental to this end because they are among the key drivers of the energy sector's growth. This study performs the first systematic literature review of renewable energy business models in Africa to assess the types, why they are adopted, and factors affecting their viability. It also investigates whether the value created translates into social, economic, and environmental sustainability. Findings show that existing research has focused on the technical, social, and economic dimensions of renewable energy business models, mainly for energy access, without analysing their environmental sustainability. The commercial viability of the business models for solar home systems and pico systems in the reviewed studies rests largely on reducing their upfront cost through innovative payment plans for customers. The profitability of mini-grids can be improved by demand stimulation through productive use of electricity in income-generating activities. Besides, incentivising the adoption of energy-using products to cover basic needs increase the average consumption and revenue per user. Unaffordability, unmet energy needs, low demand for electricity, lack of finance, business models that are unfamiliar to customers, and market immaturity are the common challenges to energy access in Africa. Our review shows that incumbent business models need to integrate environmental sustainability for a more holistic approach to informing decision-making. The synthesised evidence provided in this study can be used by policymakers to understand the needs of Africa's renewable energy sector across the three sustainability domains.

Keywords

Energy access; social value; economic value; environmental sustainability; circular economy.

Graphical abstract



Highlights

- Business models for energy access are the most common in literature on Africa
- Affordability, satisfaction & community participation are key to social value of business models
- Incumbent business models are insufficient to deliver the social value
- Environmental impacts of business models are a research gap

3.1 Introduction

Sub-Saharan Africa will triple its renewable energy capacity by 2030 to account for most of the new global additions if all nationally determined contributions are met (IRENA, 2019). The forecasts come at a time when the continent is endeavouring to achieve universal access to reliable, affordable, and modern energy by 2030 and increase renewable energy consumption in end-use sectors. Electricity access in Sub-Saharan Africa is still low, with about 54% of the population being unserved (IEA, 2021), while 85% has no access to clean cooking technologies (United Nations, 2021). According to IEA (IEA, 2019), Africa has great potential to be the first continent to base a significant portion of its economic and industrial development on clean and renewable energy sources. The development will presumably rely on business models that serve underserved markets, drive socio-economic development, and meet environmental targets.

Business models for renewable energy in Africa are rapidly emerging to reach new markets, implement niche technologies, and respond to policy requirements. To this end, there is a broad range of highly adapted business models that are creating, delivering, and capturing social, economic, and environmental value. At the same time, these business models keep evolving for various reasons. First, they evolve to offer new value propositions (i.e., the reasons for consumers to choose a company's products and services), for example, consumer financing to incentivise the uptake of renewable energy (Guajardo, 2021), or promote energy security (Yang and Yang, 2018). Second, business models evolve to capitalise on emerging business opportunities that increase renewable energy use and, hence, the companies' revenue (Cabanero et al., 2020). Third, business models evolve to respond to stringent environmental regulations aimed at decarbonising power generation (e.g., Moner-Girona et al., 2018).

Past research efforts demonstrate the diffusion (Muchunku et al., 2017), trends (Ford and Hardy, 2020), viability (Mukisa et al., 2021), and drivers (Umoh and Lemon, 2020) of these business models for different markets on the continent. However, only a few studies (e.g., Kizilcec and Parikh, 2020; Rasagam and Zhu, 2018) have performed literature reviews of renewable energy business models in Africa so far. These reviews have focused mainly on business models for solar energy, primarily solar home systems and providing energy access.

The themes in these reviews are summarised as socio-economic development, technology innovation, policy, and viability.

This study builds on the existing work to take stock of the incumbent business models for diverse renewable energy sources covered in literature to critique whether their intended products, services, or attributes create the intended value. Hence, the first objective of this study is to offer an in-depth analysis of the status quo of renewable energy business models in Africa to understand why they are adopted and the factors affecting their viability.

Once value propositions are created, they are monetised and delivered to customers for social and economic gains. At the same time, the value creation and delivery process translate to significant environmental impacts. The impacts are positive during the use stage when renewable energy displaces fossil fuels (McGee and Greiner, 2019) or negative occurring throughout the life cycle of renewable energy technologies e.g., ecotoxicity, pollution, resource depletion, climate change, and exposure to carcinogens and non-carcinogens (Mukoro et al., 2021). For example, a jatropha bioenergy system that converts fallow land has a climate change potential (CCP) of 172.0 g CO_2 eq./kWh which is higher than the CCP of converting cropland i.e., 66.7 g CO_2 eq./kWh (Almeida et al., 2015). In a different study (Al-Behadili and El-Osta, 2015), the CCP of a Libyan wind farm was found to be 10.5 g CO_2 eq./kWh. The insights into the environmental impacts of business models for renewable energy are scarce because this type of research is not yet fully developed. This study seeks to identify whether incumbent business models for renewable energy in Africa address these concerns. Therefore, the second objective of this study is to evaluate whether the value propositions deliver social, economic, and environmental value. In this context, this study performs a systematic literature review to answer the following research questions:

> RQ1. What types of business models for renewable energy are adopted in Africa and what factors affect their viability?
>
> RQ2. Do these business models deliver social, economic, and environmental benefits?

This paper is the first review article that investigates business models for diverse renewable energy sources in Africa as covered in existing research. It contributes to the wider literature on the topic by providing synthesised empirical evidence that can be used to evaluate the needs of the sector beyond Africa. This study also provides an understanding of the extent to which different business models for renewable energy in Africa integrate the three dimensions of sustainability. This paper can steer decision-making to improve the performance of the incumbent and future business models.

This paper is organised as follows. Section 3.2 provides a detailed description of the method used to perform the systematic literature review. It covers the search strategy, the inclusion criteria, and the framework used in the analysis of the results. Section 3.3 analyses the types and archetypes of business models of renewable energy, and their social, economic, and environmental sustainability. Section 3.4 discusses the implications of the findings for a broader understanding of Africa's renewable energy sector followed by the conclusion and recommendations for future research in Section 3.5**.**

3.2 Methods

3.2.1 Selection of studies

A systematic literature review was performed to identify and analyse published studies of business models of renewable energy in Africa following a systematic review protocol (e.g., Davis et al., 2014; Snyder, 2019). Broader literature on renewable energy business models was reviewed to derive keywords and synonyms that are relevant to the research questions. Keywords search was performed in Scopus, Google Scholar, and Web of Science, using the following search string combinations:

- "Business models" AND "renewable energy" AND "Africa";
- "Business models" AND "renewable energy" AND "name of an African country (search string for all African countries was performed using the given combination)";
- "Business models" OR "words that are synonymous with business models" (see next paragraph) AND "renewable energy" AND "name of specific renewable energy source or technology".

In this review, the phrase "business model" was selected as a keyword to find information about the elements of business models that would help answer the research question. The search was initially restricted to the keywords in the first search string. Thereafter, the search criteria were expanded by using general terms like “solar energy”, “wind energy”, “hydropower”, “bioenergy” or names of specific African countries to optimise the results. Keywords that are synonymous with business models for energy access and renewable energy in Africa were also used e.g., “pay-as-you-go”, “fee-for-service”, “contract farming”, and “power purchase agreement”. The limitation of the search strategy in this study is that it may exclude other relevant references that use different terms hence may affect the recommendations.

The next step was to select the final sample, based on relevance to the inclusion criteria. First, the authors of this review cross-checked the studies to remove duplicates. They identified 163 studies when the search was performed in November 2021. Second, the authors screened the title, abstracts, and keywords of the articles to determine their relevance to the topic and select candidate papers. Third, the candidate papers were read to select the final sample. Ninety-six studies were excluded from further analysis because they did not explicitly address business models of renewable energy in Africa.

The keywords and synonyms used in this study were based on the two research questions specified in the previous section. Only papers that sufficiently discussed renewable energy within the framework of business models were included in the sample. For example, several significant studies on the social and environmental aspects of renewable energy that could potentially affect the recommendations were considered out of scope because their analyses excluded business models. SI Table A 4 gives a breakdown of the search strings that were used and the number of articles that came up. Due to the low number of studies, time filtering was not applied as a selection criterion. All studies that came up in search results were included in the sample provided they met the inclusion criteria.

Sixty-seven studies were finally selected for review (see SI Table A 5) after meeting the following inclusion criteria:

- Peer-reviewed and conference papers published in English;
- For studies conducted for multiple locations around the world, at least one of the case studies must be for an African country; and
- Studies that address business models of renewable energy in Africa as part of their broad objectives on the condition that business models are adequately discussed.

The following exclusion criteria were used:

- PhD and Masters theses, handbooks, book chapters, reports, and other grey literature were not included in the literature review; and
- Studies that (i) do not explicitly cover business models for renewable energy in Africa or (ii) aggregate results of African case studies with those from other regions of the world were excluded.

3.2.2 Business model types and archetypes

The business model concept described by Osterwalder and Pigneur (2010) was chosen for this review. This concept has been successfully applied as an analytical tool for renewable energy (e.g., Richter, 2013). This systematic literature review was structured; it applied a specific framework described in section 3.2.3 and research questions to identify themes in the reviewed studies. The selected studies in the final sample were reviewed to identify similarities and differences and extract information about the renewable energy technologies and applications, country of study, themes, sector (i.e., off-grid or on-grid), and business models (data extraction table in SI Table A 5).

The business models identified in the studies were categorised into the utility-side and user-side types, to give an overview of the status quo of research on renewable energy business models in Africa (SI Table A 5). Business models of off-grid or on-grid renewable energy systems that are located on the customer's property or close to the end-user are classified as customer-side business models (Richter, 2012). In the present article, the phrase user-side business model is used instead of customer-side to go beyond purchases and cater to the social dimension of using the technologies. This review classified business models as utility-side if their focus was on large-scale renewable energy systems that generate and feed bulk energy into the central grid (Richter, 2012). In the utility-side business model, there is no self-consumption of energy or interaction with the end-user.

For each type, business model archetypes were systematically derived based on extensive categorisation examples (e.g., Tukker, 2004). Firstly, the studies in the sample were scanned to identify the common themes in the business models. All business models, except bioenergy supply chains and cash sales without product maintenance, satisfied the criteria of product-service systems (PSS) categorisation. PSS is designed to sell the availability and function of products and servicesusing models that are product-oriented, use-oriented, and result-oriented (Tukker, 2004). Secondly, archetypes were derived for each PSS category. Some of the reviewed studies explicitly defined their business model archetypes e.g.,fee-for-service for rented products rent-to-own or pay-as-you-go for product sales, store-on-grid for prosumer solutions, electrification seeds, etc. These were placed in the respective PSS categories. For the remaining studies, the approach to creating, delivering, and capturing value was used to define archetypes based on the examples given in the literature e.g., pay-per-service unit for result-oriented PSS.

Less than 10% of the studies in the sample investigated outright purchases and layaway sales although alongside PSS business models. The scope of bioenergy business models in the sampled studies was either biomass supply chain upstream (i.e., farming models) or integrated value chains from feedstock production to energy use. In the former, the supply chains were not straightforwardly categorised as PSS because the end-use was unknown. In this case, they were grouped as farming models with archetypes such as contract farming, hybrid models, and plantations (e.g., Maltitz et al., 2014). The integrated value chains met the criteria for PSS and were grouped as such. There are several areas of overlap in business models, hence, different categorisation criteria can be used e.g., stakeholders, ownership, value propositions, scope, market factors, scale, etc. In this study, the archetypes were derived based on elements of business models e.g., value proposition.

3.2.3 Theoretical framework: business model canvas

The business model canvas was used to analyse the business model types and archetypes. Nine blocks of business models were extracted from the business model archetypes i.e., value proposition, key partnerships, key activities, key resources, customer segments, customer relationships, channels, revenue streams, and cost structure. Extraction of the blocks provided a structured way of analysing the internal and external aspects of business models. Some studies explicitly defined the business model blocks (e.g., Gabriel and Kirkwood, 2016). For the remaining articles, phrases that are synonymous to the business model canvas were used to identify the blocks for each archetype e.g., ‘customer’, ‘end-user’, ‘payments’, and ‘power purchase agreements’ among others.

The nine blocks of a business model were then grouped into the following four elements to simplify the analysis:

- Value proposition: product or service offering;
- Demand-side: customer segments, customer relationships, and channels;
- Supply-side: key partnerships, key resources, and key activities; and
- Financial aspects: revenue model and cost structure.

3.3 Results

3.3.1 User-side business models: overview

The first research question of this study is to evaluate the status quo of business models in the reviewed studies and assess their viability. An analysis of the 67 studies shows that business models for distributed off-grid renewable energy have received more research attention (93% excluding studies on both user- and utility-side) (Table 2). In particular, business models examine the viability of off-grid PV solutions. Off-grid solar PV systems represented in the reviewed studies comprise pico-PV systems (typically 1-10 W), solar home systems (typically 10-1000 W), micro-grids (typically 1-50 kW), and mini-grids (typically 50 kW-1 MW). The multitier framework that measures access based on capacity, availability, duration, reliability, affordability, quality, and safety (Bhatia and Angeleou, 2015) is used to measure the level of access in several of the reviewed studies (e.g., Barry and Creti, 2020; Knuckles, 2016; Muchunku et al., 2017). Table 2 shows that there are slightly more studies on solar home systems and pico systems than mini-grids for off-grid applications with case studies mostly drawn from East Africa (about 50% of the studies). This observation of research focus can be attributed to East Africa being the pioneer of innovative business models that disseminate these systems in underserved markets (IEA, 2017) to meet the growing demand (IRENA, 2021).

A comparison of the studies in the sample from a regional perspective gives insights as to why there are regional disparities in the diffusion rate of user-side technologies. For example, on the one hand, business models for off-grid solar PV in Kenya have been relatively successful because of government subsidies, tariff relief, and private sector investment (Amankwah-Amoah, 2015). On the other hand, high lending interests and PV module price in Kenya coupled with unfavourable tariff regimes is a barrier to the commercial viability of grid-tied industrial-scale prosumer business models (Mukisa et al., 2021). Of all PV system applications in Africa, solar home systems have a larger market share in Africa due to market pull effects unlike technology-push in developed countries (Rasagam and Zhu, 2018). Indeed, capitalising on the high market penetration of mobile money in East African countries like Tanzania has quickened the diffusion of pay-as-you-go business models for solar home systems (Rolffs et al., 2015). Conversely, West Africa has relatively slow diffusion rates because uptake of mobile money is still low (Barry and Creti, 2020). In subsistence markets, the high upfront cost of renewable energy technologies and the absence of well-established distribution networks to the last mile are among the factors for the low spread of energy access business models (Scott, 2017).

Compared to other developing countries globally, the ease of doing business in Africa was found to be low due to regulatory barriers and insufficient financial support, thus, necessitating a larger number of simple than complex business models (Gabriel and Kirkwood, 2016). Simple business models operate at the initial stages of the life cycle of a renewable energy project i.e., technology distribution e.g., of solar home systems (Da Silva et al., 2014) which are the numerical majority in the sample. Conversely, complex business models operate at the advanced stages and entail large infrastructural projects. Almeshqab et al. (2019) conclude that an enabling policy environment, continuous technical support, a viable financial model, and flexibility in technical options are prerequisites for the viability of first-time energy access business models.

Table 2: Summary of the business models and value propositions in the reviewed studies

RET	Business model type	Category	Business model archetype	No. of studies	Value proposition
Hybrid (solar PV- wind turbine micro-gid)/off-grid	User-side	Infrastructure operation & technology distribution	PSS: renting (fee-for-service)	1	Renting portable battery kits that are charged at a community energy kiosk.
Hybrid (solar PV- diesel generator micro-grid)/off-grid	User-side	Infrastructure operation & technology distribution	PSS: renting (fee-for-service)	1	Renting portable battery kits that are charged at a community energy kiosk.
			PSS: pay-per-service-unit and consumer financing	1	Tier 4 level access, a financing plan for energy-using appliances, electricity demand stimulation, and productive use.
			PSS: pay-per-service-unit (electrification seed)	1	Prosumers generate electricity for captive use and retail to end-users.
Solar PV: mini-grids/off-grid	User-side	Infrastructure operation	PSS: pay-per-service-unit	5	Tier 4 level of access, consumer appliance financing, electricity demand stimulation, and productive use.
			PSS: pay-per-service-unit (KeyMaker model)	2	Productive use of electricity in agro-processing for economic gain.
Solar PV: mini-grids/on-grid and off-grid	User-side	Ownership	PSS: pay-per-service-unit: community ownership, private ownership, operator business model, hybrid ownership, and utility ownership	2	In the private ownership model, the developer builds, owns, and operates the system. In the operator model, a private company operates mini-grids on behalf of the community and sells electricity in bulk to entrepreneurs or end-users. The hybrid model is a partnership between multiple entities while in the utility model, a utility company owns the generation and distribution system.
Solar PV: pico systems and SHS/ off-grid	User-side	Technology distribution	PSS: Pay-as-you-go (rent-to-own) & consumer financing	12	Pay-as-you-go model credit plan incentivises uptake of SHS and pico systems to users with a low purchasing power.
			PSS: renting (fee-for-service) & consumer financing	7	Energy companies rent and install SHS, portable battery kits, and energy-using products on the property of users.
			PSS: performance contracts	1	Households choose energy access targets and performance contracts they wish to implement e.g., adoption of solar home systems.

			PSS: pay-per-service-unit and (multispecies swarm electrification)	1	Interconnected SHS to create a microgrid aimed at generating more electricity to power large electric loads.
Solar PV: off-grid mix (pico systems, SHS, solar mini-grids)/ off-grid	User-side	Infrastructure operation & technology distribution	PSS: pay-as-you-go (rent-to-own) & pay-per-service-unit	1	A combination of aforementioned off-grid electrification approaches to meet varied user needs.
			PSS: pay-as-you-go, leasing, renting (fee-for-service), & pay-per-service-unit	4	A combination of aforementioned off-grid electrification approaches to meet varied user needs.
Off-grid mix: SHS, solar mini-grids, hydropower micro-grids	User-side	Infrastructure operation & technology distribution	Energy storage	1	Electrical energy storage for hydropower and PV micro-grid.
Solar PV / on-grid	User-side	Infrastructure operation	PSS: Prosumer, store on-grid (pay-per-service-unit), and grid-connected micro-grids	5	Increased user engagement in energy production, electrification of end-use sectors using microgeneration, peer-to-peer trading, and low energy bills. In the store-on-grid approach, an aggregation of prosumers stores electricity in a common grid-connected battery for future consumption before feeding surplus power to the grid.
		Digitalisation & flexibility options	PSS: smart grids and virtual power plants (prosumer)	2	Smart grid integration for optimised generation and system efficiency. Virtual power plants generate revenue for prosumers.
Solar PV/ off-grid and on-grid	User-side	Infrastructure operation & technology distribution	Public sector model, private sector model, and aid model	1	The focus of these business models is ownership and financing.
Bioenergy: first-generation biofuel/ off-grid	User-side	Farming models & infrastructure operation	Contract farming (outgrower schemes)	5	Bioenergy company contracts many small-scale farmers to cultivate energy crops under outgrower contracts.
			Farming: plantation model, contract farming, hybrid models, & joint ventures	3	The plantation model provides centralised bioenergy crop production while contract farming is based on outgrower schemes for feedstock delivery. The hybrid model provides a combination of large and small-scale farming while joint ventures give communities shares in bioenergy companies in exchange for land.

			Smallholder farming and supply-chain management	2	Charcoal production, distribution, and retail to end-users.
		Technology distribution	Outright purchase, servitisation: renting (fee-for-service) & captive use.	3	Biomass pellets purchase contracts, leasing and selling micro-gasification cookstove. The cookstoves are leased when households cannot afford the purchase price.
Bioenergy: biogas micro-grid/ off-grid	User-side	Infrastructure operation	PSS: pay-per-service-unit and captive use	1	Affordable clean energy that is cheaper than alternative traditional fuel.
Hydropower/ on-grid	User-side	Infrastructure operation	Community ownership with operator business model	1	A local community and equity investors co-fund a hydropower project to create a special purpose vehicle managed by a private operator.
Wind turbines/ on-grid	Utility-side	Integrator & infrastructure operation	PSS: engineering procurement and construction, leasing & independent power producers	2	Manufacturers provide turnkey solutions and services throughout the lifecycle of the projects. In some cases, the manufacturers implement the leasing model and retain ownership of the turbines.
Renewable energy mix/ off-grid and on-grid	User-side & utility-side	Infrastructure operation	PSS: independent power producers	2	Increased competition in electricity generation and distribution.

PV- photovoltaic; RET-renewable energy technology; SHS- solar home system

3.3.1.1 Delivery of energy services to users: Product Service System

Product Service System (PSS), defined as the provision of tangible goods and intangible services (Tukker, 2004) has featured prominently in the reviewed studies (i.e., 53 studies). The studies demonstrate applications for the three main sub-types of PSS: (i) product-oriented (selling renewable energy and providing maintenance services), (ii) use-oriented (renting and leasing renewable energy systems, and (iii) result-oriented (selling electricity).

3.3.1.1.1 Product-oriented PSS: pay-as-you-go (rent-to-own)

In the reviewed studies, the pay-as-you-go business model is for frugal innovations i.e., simple low-cost products and services (e.g., pico PV systems) designed for low-income households in Africa. The value proposition for these business models is providing simple and affordable plug-and-play systems and end-user financing on a rent-to-own basis to reduce barriers to adoption. The reviewed studies highlight the popularity of the pay-as-you-go business model (Table 2) (e.g., Guajardo, 2021; Kizilcec and Parikh, 2020; Ogeya et al., 2021). A common theme of these business models is their user-centric approach to energy access. The pay-as-you-go payment model is centred on the users' ability to pay for first-time access, the energy expenditure pre-electrification, and the sociocultural practices of payment. Most of the reviewed studies (e.g., Guajardo, 2021) conclude that the value created by pay-as-you-go models depends on the ability of energy companies to meet users' energy needs at a cost that is lower, over time, than alternative fuels. Findings show that while this strategy is advancing electrification targets, especially in rural areas, the upfront cost of solar home systems is still prohibitive for people with low purchasing power (Bensch et al., 2018; Scott, 2017). Thus, the affordability and access gap further segment the market for already underserved customers.

End-user financing and flexible repayment terms are the competitive advantages of the pay-as-you-go business model over other non-PSS product-centred business models that transfer ownership to users. For example, the over-the-counter model for outright purchases (Muchunku et al., 2017) and the layaway model whereby users pay a deposit for a product to have it held for pickup when the full price is paid (Sloughter et al., 2016). Considering that the premise of end-user financing in the pay-as-you-go business model is to remove barriers to energy access, users' resistance to the value proposition has implications on the timelines for achieving electrification targets. For example, a community in Zambia preferred to switch from a newly introduced pay-as-you-go model which gives instant access to a more familiar layaway model (Sloughter et al., 2016). Likewise, low user compatibility with the payment plan increases incidences of defaulting and reverting to initial energy sources like kerosene (Barrie and Cruickshank, 2017). In such cases, the commercial viability of the pay-as-you-go business model is threatened and businesses are compelled to adapt to the changing user habits.

The potential of digitalisation in fast-tracking energy access has been explored (Bisaga et al., 2017). Energy companies are beginning to take advantage of digitalisation to improve the functionality of their products. For example, BBOXX developed a Smart Solar platform to remotely monitor the performance of its solar home systems and track repayment in Kenya and Rwanda. Remote activation and deactivation seem to be the preferred method of guaranteeing consistent repayments for solar home systems in the reviewed studies. Some of the reviewed studies (e.g., Barrie and Cruickshank, 2017) highlight the limitations of the rent-to-own payment plan of the pay-as-you-go business model. The risk of default is high when users (i) rely mostly on alternative sources of energy and use solar home systems for backup, (ii) are unaccustomed to long repayment plans, (iii) do not understand the terms of the contract e.g., access during the payment period and ownership once payments are completed, (iv) seasonal income in farming communities, and (v) users failing to keep track of repayment frequencies (Barrie and Cruickshank, 2017). Guajardo (2021), found a low default rate of 7% to 11% due to remote locking of the solar home systems whenever payments were delayed. There is a strong correlation between access to grid electricity and high defaulting on pay-as-you-go repayment since the solar home systems are only used for backup during outages (Barry and Creti, 2020). Regional disparities in economic development in a country also increase the likelihood of non-payment (ibid).

3.3.1.1.2 Use-oriented PSS: lease and rent

The leasing and renting business models for energy access have been studied in about 19% of the studies (including those that analyse multiple business models) (e.g., Bacchetti et al., 2016; Emili et al., 2016). There are areas of overlap in these business models and pay-as-you-go. Similar to the pay-as-you-go model, the value proposition of the leasing and renting approach is to eliminate barriers to the diffusion of renewable energy systems by excluding down payments and charging users for access rather than ownership. For PV applications, the leasing model creates value by installing solar home systems on the property of a user in exchange for regular payments for the energy consumed or the system's uptime over a lease term. There are two approaches to renting (i.e., fee-for-service) in the reviewed studies. In the first approach, users get access to portable battery kits that are charged on a need-basis at a central energy kiosk powered by a solar PV mini-grid (e.g., Acker et al., 20014). In the second approach, users rent solar panels, lighting appliances, and batteries from energy companies (e.g., Sovacool, 2013).

The rationale for implementing leasing and renting business models in underserved markets is to address the affordability-access gap in low-income markets in addition to reducing business risks. Several studies (e.g., Muchunku et al., 2017) point out that providing end-user finance to users who have no income details or credit history ranks the pay-as-you-go business model as a high financial risk. Conversely, the financial risk of the leasing and renting business model is moderate, associated with paying service providers, while the risk to users is very low owing to routine maintenance services (Friebe et al., 2013).

A key finding from the sampled studies is the viability of the leasing and renting model. Studies (e.g., Ellegård et al., 2004) show that in Zambia, the leasing model is more favourable to households that have higher purchasing power because the use of solar home systems is costlier than dry cell batteries, candles, and kerosene. Likewise, the renting business model in the same country is unattractive to users because it increases household energy expenditure and consequently most batteries are unrented a short while after rollout (Sloughter et al., 2016). The viability of these business models varies across markets depending on the predominant financing approaches e.g., leasing, credit, or cash sales (Kizilcec and Parikh, 2020). Arguably, incumbent business models for energy access alone are essential but not sufficient for universal electrification. For this reason, subsidies may be necessary to incentivise the adoption of solar home systems (Kizilcec and Parikh, 2020). However, subsidising energy companies to cover their costs and provide subsidised products does not guarantee substantial benefits if the fee is still too high for users (Bensch et al., 2018).

The theme of access over ownership emerges from the reviewed studies of leasing and renting business models. A comparison of energy access business models highlights the preference of pay-as-you-go over leasing and renting among users because the former leads to ownership (Muchunku et al., 2017). From the energy companies' perspective, cash sales and credit are most preferred to leasing and renting because users are less likely to default on payments that lead to ownership (Friebe et al., 2013). Although the risk of theft was found to be low, users can be deterred by the responsibility of paying for stolen costly systems in their possession (Ellegård et al., 2004).

3.3.1.1.3 Results-oriented PSS: pay-per-service-unit

The results-oriented PSS business model in the sampled studies (about 30% of the sampled studies including those that analyse multiple business models) is the pay-per-service unit for the generation and sale of electricity. The value proposition of the business models that satisfy this criterion include:

- First-time electricity access in off-grid areas served by micro-and mini-grids (e.g., Lukuyu et al., 2021);
- Swarm electrification i.e., solar home systems installed on users' property are interconnected to form low-voltage micro-grids (Kyriakarakos and Papadakis, 2019);
- Productive use of electricity (Cabanero et al., 2020);
- Electrification seeds i.e., prosumers sell surplus electricity to neighbouring households and businesses to displace diesel use (Huber et al., 2021);
- Grid decarbonisation e.g., prosumers sell surplus electricity to the grid (e.g., Sewchurran and Davidson, 2021);
- System optimisation e.g., a cluster of prosumers store electricity on a central government-owned battery to optimise self-consumption before selling the surplus to the grid (i.e., "store-on-grid"). The value propositions are decarbonisation of distributed generation, cost-effective financing of prosumer business models, and energy cost savings (Mukisa et al., 2021);
- Digitalisation and energy efficiency e.g., prosumer virtual power plants for energy management and revenue generation (Venkatachary et al., 2017); and
- Electricity storage in batteries paired with micro-and mini-grids to cater to peak demands or store energy from on-site generation (Mandelli et al., 2016).

The main focus area of delivering the value propositions in the sampled studies is viability. A general finding is that the viability of enabling first-time electricity access in new markets depends on the existing infrastructure, policies, financing, and technical aspects. Pre-existing social infrastructure and social enterprises positively influence the commercial viability of mini-grids in remote rural areas (Almeshqab and Ustun, 2019). A combination of anchor clients and users with light electric loads e.g., households is crucial to the profitability of developer-owned mini-grids (Ogeya et al., 2021). One study points out that uniform tariffs are a key barrier to private sector mini-grids because they do not reflect the high capital cost of implementing electrification projects in remote rural low-income markets (Rasagam and Zhu, 2018). Anchor clients, therefore, create a reliable and predictable electricity demand pool because of their high consumption and are attractive to private sector developers (Knuckles, 2016).

The demand for electricity in off-grid areas is generally low pre-electrification (Troost et al., 2018) and when combined with the high capital cost, it affects the profitability of mini-grid businesses. Several studies (e.g., Cabanero et al., 2020; Lukuyu et al., 2021) investigate the effectiveness of demand stimulation and productive use strategies employed by micro-and mini-grid developers to build power demand. On the one hand, supplying energy using appliances as part of the value proposition to users increases the average consumption and revenue per user (Lukuyu et al., 2021). On the other hand, these appliances can stimulate electricity use but do not guarantee sustained electricity demand (Ogeya et al., 2021). Supplying these appliances must be paired with consumer engagement to mitigate the risk of energy stacking or reverting to previous sources of energy (Ogeya et al., 2021). Productive use value propositions that are tailored to the main economic activity in the community, e.g., processing agricultural outputs for farmers. lowers the levilised cost of electricity (LCOE) and increases cash flow (Cabanero et al., 2020). Indeed, understanding the energy needs and consumption patterns of the local community would be beneficial to the design of demand stimulation and productive use strategies (Batidzirai et al., 2021).

Financial constraints of grid densification e.g., fixed costs of service drops to businesses and households situated close to power distribution networks create opportunities for mini-grid connections because they are less costly and easy to scale (Alstone et al., 2015). However, micro-and mini-grids are also constrained by their technical viability and cannot serve all customers in off-grid areas. In the case of swarm electrification, the technical viability in Sub-Saharan Africa is low due to households being dispersed in most rural areas

(Kyriakarakos and Papadakis, 2019). Likewise, mini-grids are only technically and commercially viable in highly populated areas (Muchunku et al., 2017). The incumbent business model mix for off-grid technologies complements each other to create value for distinct user groups. The smaller systems are more tailored to users that do not qualify for mini-grid connection i.e., have a low-ability-to-pay, live beyond the mini-grid distribution radius, or are in sparsely populated locations.

Unlike off-grid applications, studies on grid-connected renewable energy applications are scarce in the sample. They are only considerably covered in five studies (e.g., Mukisa et al., 2021; Sewchurran and Davidson, 2021). The value proposition for these businesses occurs at the business-to-business level between prosumers and the utility. Tax benefits, availability of funding, regulatory reforms, and favourable tariff structures are cited among the key incentives for the success of prosumer value propositions in South Africa (Sewchurran and Davidson, 2021). Conversely, unattractive feed-in-tariffs in most African countries and the introduction of more complex energy auctions by governments deter prosumer business models (Mukisa et al., 2021). A new store-on-grid scheme based on innovative power purchase agreements was found to have more potential than feed-in-tariffs in African countries that have time-of-use tariffs in place (Mukisa et al., 2021). The study concluded that the scheme was only viable in four countries (e.g., Togo and Namibia) out of 13 because of low LCOE, low price of PV module, and favourable lending rates. However, government subsidies on time-of-use tariffs in most African countries hinder more accurate assessments of the commercial viability of the store-on-grid scheme. For community-owned mini-grids, leveraging private sector expertise to operate special-purpose vehicles and creating joint ventures with equity investors was proven to de-risk business models and enhance their commercial viability (Njogu et al., 2017). Prosumer virtual power plants have only been covered by one study for Botswana (Venkatachary et al., 2017), therefore, the regional viability of the business model cannot be deduced. Nevertheless, the success of the business model depends on utilities' effective coordination and pooling power purchases, the flexibility of aggregators to bid, and network management (Venkatachary et al., 2017).

3.3.1.1.4 Farming models for bioenergy

Four of the fifteen studies on bioenergy assess business models for electricity and heat generation in gasifiers (e.g., Buchholz et al., 2012), biogas micro-grid (Hamid and Blanchard, 2018), and outright purchase of biomass pellets combined with renting micro-gasification cookstoves (Jagger and Das, 2018). The remaining studies focus on farming and feedstock procurement models summarised below:

- Smallholder farming model and independent large-scale producers whereby farmers grow and sell energy crops to bioenergy companies (Brüntrup et al., 2018; Bryant and Romijn, 2014);
- Corporate plantations model is based on centralised ownership of large hectares of land on a freehold or concession basis. This business model is ideal for capital-intensive bioenergy crops (Maltitz and Setzkorn, 2019);
- Energy or fuel security whereby companies, large-scale farmers, and smallholder farmers cultivate bioenergy crops to meet their energy needs (Maltitz and Setzkorn, 2019);
- A hybrid model of small-scale and large-scale farming whereby both the farmers and corporates own resources e.g., land (Hultman et al., 2012; Maltitz and Setzkorn, 2019);
- Contract farming models through out-grower schemes whereby farmers and a processing plant sign a contract for energy crop delivery, feedstock purchase agreement, and sometimes provision of farm inputs (e.g., German et al., 2011; Maltitz et al., 2014).
- Small-scale farming for charcoal production, distribution, and retail (Nigussiea et al., 2021; Roos et al., 2021).

The overall objectives of bioenergy production in most African countries are petroleum blending, producing ethanol for heating, exports, and electricity production (Maltitz and Setzkorn, 2019). The value propositions in outgrower schemes, smallholder farming, and hybrid models are to the farmers, unlike corporate plantations whereby bioenergy companies are vertically integrated and generate their feedstock for energy conversion. Household-led biomass enterprises (e.g., focusing on charcoal) supplement household income and improve rural livelihoods (Roos et al., 2021). However, even with improved management of forests, the business case in countries like Kenya failed, following the ban on charcoal to prevent forest degradation and protect indigenous tree species (Roos et al., 2021).

The concerns about the implications of bioenergy crop production on food security in Africa have a direct bearing on the viability of the business models and value propositions. Contracting farmers to cultivate jatropha as hedgerows on unused boundary land in Tanzania was found to eliminate the competition for nutrients and water and generated additional income for farmers (Bryant and Romijn, 2014). However, the yield for hedgerows is low and a Zambian case study found that farmers preferred intercropping jatropha with food crops such as sweet potatoes or beans for more yield (German et al., 2011). Whereas jatropha and sugarcane remain the preferred feedstock in most African countries (Maltitz and Setzkorn, 2019), jatropha was banned in South Africa due to its invasive nature in preference for more beneficial and profitable feedstock such as sugarcane and sunflower (Hultman et al., 2012). Indeed, several studies (e.g., Maltitz and Setzkorn, 2019; Maltitz et al, 2014) conclude that the jatropha business model is less profitable for reasons such as lack of financing, poor yield, the inability of corporates to fulfil contractual agreements, and low-value seedcake because of its toxicity. Besides, low income from the sale of feedstock, food security, and in some cases unfavourable contract terms (e.g., land availability due to long contracts of up to 30 years), dissuade farmers from participating in outgrower schemes (Bryant and Romijn, 2014; German et al., 2011).

Findings show that outgrower schemes are preferred when the land tenure systems (e.g., customary tenure) and different maturity rates of certain crops disincentivise plantation farming (German et al., 2011). However, a study of 23 bioenergy projects in Southern African countries found the plantation model implemented by large corporates the most common (Maltitz and Setzkorn, 2019). The viability of this farming model is determined by land requirements for commercially viable yield, the land tenure system, farmers' participation, technology requirements for feedstock processing, and capital (Hultman et al., 2012).

3.3.2 Utility-side business model

Utility-scale business models have not received as much attention as user-side business models in the reviewed studies (Table 2), which could be attributed to the heightened focus on access in Africa. Two studies are exclusive to utility-scale renewable energy systems (Campbell et al., 2013; Umoh and Lemon, 2020), while two combine both utility- and user-scale in their analyses (Amankwah-Amoah, 2015; Budzianowski et al., 2018). Despite the low number of studies, they reflect representative features of utility-scale renewable energy in Africa and provide sufficient information to answer both research questions. The four studies explore diverse case studies but the main similarities are the drivers and barriers to renewable energy projects in Africa.

The value propositions can be summarised as the delivery of large-scale renewable energy infrastructure through engineering procurement and construction contracts (e.g., Campbell et al., 2013) and grid supply of low-carbon electricity by independent power producers (e.g., Budzianowski et al., 2018). Among the drivers of implementing large-scale renewable energy projects in the studies, private sector involvement through private-public partnerships was found to be necessary for executing the value propositions. Typical models for private-public partnerships are build-transfer turnkey solutions and build-own-operate based on power purchase agreements. These partnerships are stated to sustain the renewable energy sector in countries like Nigeria (Amankwah-Amoah, 2015) and are crucial to de-risking complex infrastructural projects through approaches like co-financing (Budzianowski et al., 2018). All case studies mention that renewable energy development is disadvantaged by financial constraints. Besides traditional financing pathways, the entry of vertically integrated multinationals, mainly from China, that provide project finance in addition to low-cost projects, is making wind energy projects feasible in Africa (Campbell et al., 2013).

There are several key barriers identified in the sampled studies that threaten the viability of large-scale renewable energy generation in Africa. First, the commercial viability of capital-intensive projects like wind farms depends on the market orientation and maturity e.g., regulations incentivising competitive pricing. The lack of streamlined policy and frameworks that are at par with market advances increases the risk of wind energy projects (Umoh and Lemon, 2020). Besides, reforms in Africa's market orientation such as strengthening the legal system, physical infrastructure, and labour market to attract investment and a skilled workforce are needed to reduce the cost of doing business in Africa (Campbell et al., 2013). Second, few local supply chains for wind energy projects increase project costs due to reliance on imports (Umoh and Lemon, 2020). In the build-transfer model executed by vertically integrated multinationals, obtaining part replacements locally during the operation phase or a pool of local skilled workforce may be problematic (Campbell et al., 2013). Third, local community structures that accord them fractional ownership of energy projects (2.5%)

and access to project revenue (1%) increase the complexity of implementing renewable energy projects (Umoh and Lemon, 2020).

3.3.3 Social sustainability

To answer the second research question, this section explores whether the value propositions go beyond delivering products and services to translate into societal benefits. Using the business model canvas as the framework for analysis, social aspects are linked to the demand-side of business models i.e., customer segments, customer relationships, and channels.

There are contradictory findings on the affordability of products and services for energy access among users. At the household level, uptake of renewable electricity rests on users' reception of the value propositions i.e., affordability, quality of light, reliability, and functionality. Although household income is initially affected by subscription fees of the pay-as-you-go, renting, and leasing models, it is offset by the relatively lower cost of switching from traditional alternatives like kerosene and reduces energy expenditure (e.g., Barrie and Cruickshank, 2017; Emili et al., 2016; Guajardo, 2021). For instance, cost savings of up to USD 10 per month for adopting fee-for-service solar home systems. In contrast, several studies show that the energy expenditure in poor households increases when they switch to the fee-for-service model, hence, unaffordable (e.g., Ellegård et al., 2004; Muchunku et al., 2017; Sloughter et al., 2016). A similar trend is noted for mini-grids whereby in some contexts, household energy expenditure reduces by up to 33% relative to pre-electrification conditions (e.g., Hamid and Blanchard, 2018), and in other contexts, unaffordability is observed (e.g., Knuckles, 2016; Ogeya et al., 2021). In some instances, household energy expenditure did not change post-electrification i.e., the cost of renting solar home systems was the same as purchasing kerosene (Bacchetti et al.,2016). Several studies that compare household expenditure for a range of energy options (e.g., Jagger and Das, 2018) show that renewable energy solutions are less costly than some alternatives but are not always the cheapest option. Petroleum products like kerosene are highly subsidised by governments; therefore, they perform better than renewable energy in cost comparisons e.g., households pay USD 0.8/ kg per day for biogas, USD 0.6/kg for kerosene, and USD 1.2/kg for firewood (Hamid and Blanchard, 2018).

The findings on affordability imply that incumbent business models for energy access can reduce inequality across social classes but at the same time further segment low-income markets. Compared to national averages, off-grid electricity is costlier than the grid because of the regressive relationship between the unit cost of electricity and consumption for off-grid systems unlike the progressive relationship for grid electrification (Alstone et al., 2015). One study found that the national grid tariff was ten times lower than that charged by a private-sector mini-grid operator per unit of electricity (Ogeya et al., 2021). Users, therefore, practice energy stacking to reduce their electricity consumption (e.g Kizilcec and Parikh, 2020) while some revert to pre-electrification energy sources when they default payments and their systems are repossessed by energy companies (e.g., Barrie and Cruickshank, 2017). In such cases, the business models for energy access are complementary rather than substitutive of pre-existing value propositions.

Effective customer relationships and channels e.g., call centres, technical assistance, and flexible payment plans aimed at understanding users' needs post-electrification have been evidenced in several studies. For example, cross-subsidies and innovative payment plans are essential to not only eliminate the affordability barrier to achieving energy equality and security but also retain customers (Budzianowski et al., 2018).

Analysis of gender aspects of energy access showed that women's livelihood does not always benefit from energy access as much as men's do. For example, an investigation of the distribution of enterprises by gender found that male-owned businesses dominate productive use of electricity in rural areas, thereby, tend to benefit more from electrification projects (Pueyo et al., 2020). Female-owned businesses typically consume less energy and are, therefore, unattractive to demand stimulation efforts of energy companies which tend to target male-dominated sectors like milling and fishing (Pueyo et al., 2020).

Similar to affordability, the reviewed studies on off-grid applications show that users' satisfaction with the value delivery post-electrification varied. For example, users' satisfaction with the services e.g., quality of light (Sovacool, 2013) increases their willingness to pay more for electricity than alternative energy sources (Ellegård et al., 2004). Besides, productive use of electricity is evidenced to improve rural livelihoods albeit to varying extents (Cabanero et al., 2020). In several studies, household income diversification e.g., from energy crop cultivation (Bryant and Romijn, 2014), employment in the bioenergy supply chains (Buchholz et al., 2012), and improved living conditions (Mahama, 2012) are cited as some of the benefits that increase users' reception of value propositions. Conversely, evidence shows that unmet expectations and unfulfilled needs in communities post-electrification due to weak customer relationships are some of the challenges of transitioning to cleaner energy sources. For example, constructing small mini-grids due to the underestimation of energy demand in communities results in pre-electrification needs not being met (Almeshqab and Ustun, 2019). Users with large electric loads are potentially restricted or unserved when mini-grids are not optimally sized (Ogeya et al., 2021). For businesses with small loads, an increase in business revenue and profitability can be cancelled out by the high cost of electricity (Ogeya et al., 2021).

Several studies conclude that energy access businesses models meet societal needs in education (Moner-Girona e al., 2018), health (Hamid and Blanchard, 2018), and gender equity (Alstone et al., 2015; Budzianowski et al., 2018), but they are not in and of themselves sufficient to satisfy all needs or effect positive social development impacts. These business models perform better when they integrate community participation to cater to culture, values, and social issues in their value propositions and customer relationships (Scott, 2017). However, community participation in business model creation in most cases is limited to awareness creation, land acquisition, and tariff setting because energy companies may claim to already know and have solutions to societal needs (Batidzirai et al., 2021). The consequence is that communities have insufficient information and a limited understanding of the business model and are less likely to benefit from it especially when customer relationships are weak (Batidzirai et al., 2021). Unmet expectations in the community are often a result of insufficient flow of information on important issues such as limitations of the project in terms of functionality and the number of people that will be served, etc (Ogeya et al., 2021).

The reviewed studies on business models for on-grid systems do not assess the social implications of the systems in great detail. A plausible reason is that in utility-scale systems, independent power producers have no interaction with end-users, hence, customer relationships occur at a business-to-business level between producers and distributors of energy. For prosumers, benefits such as energy security due to mitigating outages from unreliable grid supply and low energy bills have been realised (e.g., Mukisa et al., 2021).

3.3.4 Economic sustainability

In this section, the economic sustainability of delivering the value propositions is evaluated focusing on costs and revenue (SI Table A 5) and the overall profitability of energy companies. The capital and expenditure costs of mini-grid projects in Africa vary depending on national and local contexts and are affected by factors such as market maturity (e.g., availability of skilled workforce), customer base and their load profiles, subsidies, etc. (Moner-Girona et al., 2018). On average, the installation cost estimates for solar mini-grids in Africa are high at about USD 9.51/Wp relative to the module price of USD 0.95/Wp (Moner-Girona et al., 2018). Overall project costs for on-grid renewable energy also vary regionally but are estimated at less than USD 3,500/kW for solar PV, USD 2,500/kW for bagasse boiler, USD 2,000/kW for onshore wind, and between 2,000 and USD 4,000/kW for hydropower (Budzianowski et al., 2018).

Low electricity demand in off-grid areas and unpredictable load curves coupled with high capital expenditure are some of the factors that affect the risk-return profile of solar mini-grids in Sub-Saharan Africa (Troost and Musango, 2018). Even with a high user willingness to pay for electricity, the economic value of solar mini-grid businesses depends on the electricity demand rate (Lukuyu et al., 2021). Studies show that the LCOE can be lowered through demand stimulation, thus, making mini-grids more attractive to investors. For example, without productive uses of electricity, the LCOE of solar mini-grids in Nigeria was higher (i.e., between USD 1.2/kWh and USD 1.4/kWh) than a scenario that powered high-load machinery for productive uses (between USD 1/kWh and USD 1.4/kWh) (Cabanero et al., 2020). Prosumers switching from self-generation and consumption to supplying surplus electricity from solar systems to neighbouring households decreased LCOE by 4% (Huber et al., 2021). In on-grid solar PV systems implemented by prosumers in 13 African countries, the LCOE range was USD 0.07/kWh to USD 0.18/kWh, the upper value being recorded in countries like Kenya and Zimbabwe that have high-interest rates on loans (Mukisa et al., 2021).

The economic barrier of business models for solar home systems and pico systems is low to medium i.e., retail prices of USD 10–100 and USD 75–1,000, respectively, hence their wide market penetration (Alstone et al., 2015). Friebe et al. (2013) highlight that fee-for-service and leasing have a market potential of <70% and <50%, respectively, compared to <20% and <3%, respectively of credit and cash sales. Nonetheless, businesses are more inclined to credit and cash sales because of their low financial and technical risk. For example, the success of leasing and renting business models rest on a minimum user base of between 150 and 200 customers and a minimum capital requirement that may be unaffordable to early-stage enterprises (Ellegård et al., 2004). Adding to the capital cost are incidences of most batteries becoming faulty within a year of use instead of the intended three years due to poor maintenance and overuse (Ellegård et al., 2004). As mentioned in section 3.3.1.1 uncertainties in revenue streams occur when users default payments for rented, leased, or pay-as-you-go systems, thereby affecting cashflows.

Mini-grids powered by hydropower are relatively cheaper to operate than solar mini-grids and have more energy yield, hence, can have a more reliable revenue stream from selling electricity to the grid (Knuckles, 2016). Solar mini-grids have a moderate to high economic risk and their profitability depends on a range of factors including a well-structured value chain, the tariff model, and subsidies (Knuckles, 2016), average consumption and revenue per user (e.g., Lukuyu et al., 2021), and availability of working capital (Rolffs et al., 2015). Unattractive tariffs have been mentioned severally (e.g., Almeshqab and Ustun, 2019; Rasagam and Zhu, 2018; Troost et al., 2018) as a major hurdle to the profitability of private-sector-led solar mini-grids. Applying a uniform tariff for both private- and public-sector-led mini-grids may not be cost-competitive for the private sector due to the high cost of generating electricity per kilowatt-hour in off-grid areas. In most cases, the economic viability is influenced by external factors such as lack of subsidies and capital for early and growth-stage energy companies (Ellegård et al., 2004), perceived high risk of financing energy projects in developing countries (Rolffs et al., 2015), and lack of track records to attract traditional lending (Troost et al., 2018).

3.3.5 Environmental sustainability

All studies in this review largely interpret environmental sustainability as greenhouse gas emission reduction. This information is laid out in the introduction section in most of the studies and not investigated further besides describing the renewable energy technology of interest. Unlike the social and economic dimensions, environmental sustainability remains largely unexplored in the findings of the studies.

Only eight studies (e.g., Brüntrup et al., 2018; Buchholz et al., 2012; Moner-Girona et al., 2018) evaluate the environmental impacts of renewable energy in their findings albeit to a lesser extent. Few studies show that displacing kerosene and fossil diesel with renewable energy saves significant emissions post-electrification. For example, the climate change potential of kerosene use in households at baseline is 10^5 kg CO_2 eq./household per year compared to 10^4 kg CO_2 eq./household per year for switching to off-grid connections and 10^3 kg CO_2 eq./household per year for grid-connection (Alstone et al., 2015). Similarly, substantial emission saving of approximately 120,000 t CO_2 eq. to 180,000 t CO_2 eq. is also achieved by displacing fossil diesel with solar mini-grids that have a 20-year lifetime (Moner-Girona et al., 2018). In a biomass gasifier system, 190 t CO_2 eq./year is avoided by displacing diesel engines while biogenic emissions are offset by about 271 t CO_2 eq./year through waste heat recovery (Buchholz et al., 2012). These findings show that the use-stage of renewable energy has positive implications for climate change mitigation.

In several studies (e.g., Huber et al., 2021) solar mini-grids are coupled with diesel generators for backup power supply in off-grid electrification projects, hence, a dominant source of greenhouse gas emissions. Such hybrid systems can result in high greenhouse gas emissions if solar energy generation and use are lower than diesel generation. Maltitz and Setzkorn (2019) conclude that emissions from small-scale production of feedstock for rural development are irrelevant because of their negligible scale. Conversely, emissions from large-scale plantations for the export market are of concern if the feedstock contributes to meeting international decarbonisation targets. Other than climate change, two studies (German et al., 2011; Maltitz and Setzkorn, 2019) note land-use change impacts such as loss of biodiversity due to converting fallow land and mature forests, while Brüntrup et al. (2018) mention impacts of feedstock production on water depletion and degradation. However, these impacts are neither quantified nor the consequences discussed in detail.

Finally, several other studies briefly allude to the environmental sustainability of renewable energy business models. Friebe et al. (2013) for example mention the resource efficiency potential of PSS business models for energy access projects in Africa. However, the evidence of attribution is limited in the studies. The rationale for the environmental sustainability dimension of PSS business models is to slow resource loops by optimising their use. The social and economic sustainability dimensions of these business models are emphasised in the sampled studies to reduce barriers to adopting renewable energy technologies. Evidence shows that renting and leasing solar home systems does not necessarily translate to product life extension depending on users' perception and value of ownership. Ellegård et al. (2004) for example, found that users had a low incentive to properly maintain rented batteries. Hence, there were poor battery usage patterns and a need for replacement after less than one year of use which only heightened the recycling challenge. In a different case study, unrented batteries degraded and became faulty due to users abandoning the renting model in preference for product purchases and ownership (Sloughter et al 2016). Adopting PSS by itself does not necessarily equate to environmental benefits because of burden-shifting i.e., changing value propositions may have negative rebound effects. A multi-criteria approach that combines the business framework with life cycle assessment may be necessary to improve environmental impacts through hotspot analysis of activities on the supply-side and demand-side.

3.4 Discussion

The findings provide several lessons for viable business models for renewable energy in Africa, focusing on social, economic, and environmental dimensions. This section discusses the implications of the lessons and offers recommendations.

(i) Risk of unproven business models that are disconnected from communities

Innovation in solar PV technologies and new business models for underserved markets have become the least-cost option for energy access (REN 21, 2020). The emergence of innovative business models is designed to narrow the affordability gap and increase their diffusion in low-income markets. Yet, factors such as users' preferences, the complexity of contracts, and incompatibility with users' lifestyles (Barrie and Cruickshank, 2017) affect the profitability of the business models. In the reviewed studies, the rent or lease fee is determined by the users' energy expenditure or ability-to-pay pre-electrification. A study of the solar PV leasing business model in the United States shows that optimal lease fees should be determined by the energy yield, consumption, and number of users (Hong et al., 2018). Ideally, the optimal fees should reduce users' energy bills for the business model to be commercially viable. However, the complexity of delivering energy access projects in low-income markets must go beyond pricing to include market development strategies that do not limit community participation. A disconnect between community groups that understand their needs and energy companies that implement solutions (Batidzirai et al., 2021) does not capture socio-cultural needs beyond energy access (Batidzirai et al., 2021; Johnson et al 2019). Business models co-created together with the users may be necessary to enhance competitive advantage while integrating the voice of the community. After all, demand-side preferences are as much an impetus for innovation in business models, as are technological advancements (Horbach et al., 2012).

(ii) Need for institutional support to access finance

In the European Union, renewable energy development is driven by factors such as market liberalisation, guaranteed minimum price, competition, subsidies for emerging technologies, and well-established regulations for mature technologies (European Commission, 2017). African countries are often perceived as having a high risk of doing business (Rolffs et al., 2015) mainly due to high capital costs, high-interest rates on loans (Da Silva et al., 2014), and market maturity concerns about subsidies, tax breaks, and the availability of skilled workforce (Campbell et al., 2013). In the bioenergy sector, a major concern for investors is the influx of cheap imported feedstock that disrupts local prices and the profitability of businesses due to unstable import duties and trade restrictions (Brüntrup et al, 2018). Besides, a weak top-down approach to enforcing regulations on trade, and lengthy and costly bureaucratic processes are a hurdle to investment because investors perceive such policy environments as unstable and difficult to work in (Brüntrup et al, 2018). These issues affect the bankability of renewable energy business models and increase grant dependency. Early and growth-stage energy companies struggle to raise capital because of their risk-return profile i.e., they are too large for microfinance and too small for debt. Bundling several projects can qualify them for debt (Troost et al., 2018). Where aggregation is not feasible, catalytic funding and a pool of innovative financing schemes are necessary to navigate the complex financing landscape of energy access projects in Africa.

(iii) Unmet expectations

The findings show that the demand for electricity in off-grid areas is usually low especially when target customers do not have electricity expenses pre-electrification (Sloughter et al., 2016). Hence, a major challenge for developers is accurately estimating electricity demand and affordability. Overselling electrification projects during the pre-development phase creates expectations in target communities. Findings show that there were unmet expectations due to the construction of small capacity mini-grids relative to demand which resulted in restricted power use and limiting the number of customer connections (Ogeya et al., 2021). The energy demand post-electrification can increase exponentially, hence, a need for more accurate predictive modelling. In contract farming, the risk of farmers being stranded with unprofitable feedstock after bioenergy companies become insolvent has been evidenced (German et al., 2011). While the choice of profitable feedstock can reduce the risk for farmers, implementing contractual agreements in a policy vacuum is an investment risk that does not guarantee the protection of farmers. A study conducted in the United Kingdom found that uncertainty of returns on investment for novel feedstock and contract enforcement due to the absence of mature markets is an obstacle for farm-level production (Sherrington et al., 2008).

(iv) Environmental impacts

The evidence of the environmental sustainability of renewable energy technologies other than greenhouse gas emission savings is limited in the sampled studies. Yet, renewable energy development is responsible for significant negative environmental impacts on a life cycle basis (Aberilla et al, 2020; Gaete-Morales et al., 2018). The social and economic dimensions of business models have implications for the environmental sustainability of renewable energy but the current literature does not consider their full extent. Particularly, life cycle impacts which originate from the key activities of business models i.e., production, installation, use, and end-of-life. Previous studies show that the CCP of an off-grid hybrid solar PV-diesel generator micro-grid is significant on a life cycle basis e.g., 164.0 g CO_2 eq./kWh from a micro-grid installed in Kenya (Bilich et al., 2017). Besides, the imminent waste challenge of the growing renewable energy sector is also of concern in Africa. For example, a CCP of 37.0 t CO_2 eq./ MW was recorded in Morocco from the treatment and landfilling of a 1 GW multi-crystalline PV system (Ito et al., 2016). Recycling has been demonstrated to lower the cumulative greenhouse gas emissions of renewable energy technologies. For example, the CCP of a Libyan wind farm reduces from 10.5 g CO_2 eq./kWh without recycling to 4.6 g CO_2 eq./kWh with recycling (Al-Behadil and El-Osta, 2015). These examples drawn from case studies of renewable energy projects in Africa show that renewable energy development has significant negative environmental impacts.

A life cycle approach that integrates production and end-of-life considerations into incumbent business models will give a more comprehensive assessment of their environmental sustainability. Most of the business models in the reviewed studies focus on the use-phase of renewable energy technologies and it is unclear whether they have a linear or circular economy orientation. Business model innovation through changing the value proposition (Aspara et al., 2010) and including innovative linkages of new activities (Amit and Zott, 2012). may be necessary to integrate circular economy principles in incumbents (Mendoza et al., 2017). Business model innovation does not necessarily translate to environmental benefits (Heyes et al., 2018). It must be accompanied by life cycle assessments to quantify the degree of change across a range of impact categories such as climate change, pollution, toxicity, etc (Mukoro et al., 2021).

3.5 Conclusion

This study performs a systematic literature review to investigate renewable energy business models adopted in Africa, their viability, and to what extent they deliver on social, economic, and environmental sustainability. Research has mainly focused on energy access through small-scale decentralised off-grid solutions, particularly solar photovoltaic mini-grids, solar home systems, and pico systems. Studies of decentralised on-grid systems and utility-scale applications are few and far between. The reviewed studies reveal the technical, social, and economic factors affecting the viability of business models for renewable energy. Findings show that business models for first-time energy access are designed to reduce the barriers to the diffusion of renewable energy technologies in Africa. Their growth is driven by the presence of an underserved off-grid market, the willingness and ability to pay for energy, end-user financing, and the anticipation of lower energy expenditures among users. The attractiveness of bioenergy farming models is determined by land tenure systems, the type of feedstock, and the potential for enhancing rural livelihoods. The success of renewable energy business models is constrained by among other factors, unaffordability due to low purchasing power, incompatibility with users' preferences and lifestyles, and unmet expectations. Demand stimulation and productive use of electricity are evidenced to reduce the levilised cost of electricity and increase the commercial viability of renewable energy business models. However, factors such as high-interest rates on loans, unfavourable tariffs, financing challenges, lack of enabling policies, and market immaturity affect the economic viability of the business models.

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Chapter 4

Paper 3: Environmental evaluation of business models: The EBuM framework and its application to solar energy in Kenya

This chapter has been prepared in manuscript format and will be submitted to an appropriate journal. Targeted journal: Sustainable Consumption and Production

This paper evaluates the life cycle impacts of solar energy business models in Kenya using a new framework. Sections, figures, and tables have been renumbered to comply with the structure of this thesis. The doctoral researcher (Velma Mukoro) is the lead author of this paper. Her contributions to the paper are the conception of the study, providing ideas, acquiring and processing data, analysis, interpretation, writing, and revising the paper. The co-authors' (Dr Maria Sharmina and Dr Alejandro Gallego-Schmid and who are the lead author's supervisors) contributions are the conception of the study, critical revisions of the paper, and editing the final version for publication.

Abstract

Business models have the potential to deliver environmental sustainability in companies through innovative approaches to creating and delivering value. Business model innovation has been shown as a means to integrate circular economy principles into companies' operations. Several frameworks have been created to guide the transition from traditional to circular business models. However, there is a need for a framework that quantitatively evaluates the environmental impacts of business models to ascertain how circular such business models can become. This study presents a new framework for evaluating the Environmental performance of Business Models (EBuM). The EBuM framework consists of sequential steps of life cycle assessment, participatory decision making, and business model innovation. It enables organisations to integrate environmental considerations in their decisions and operations. The framework was tested on solar energy companies in Kenya. Life cycle assessments of the photovoltaic systems were conducted through the lens of business models of participating companies to provide insights into the hotspots of environmental impacts. Each company participated in two workshops to evaluate the potential of business model innovation in mitigating the environmental impacts of their activities. Findings showed that the environmental impacts of incumbent business models were generally higher than their circular economy-oriented substitutes. Business model innovation could, for example, lower the climate change potential by 12%–55% and the metal depletion potential by 40%–70%. While the framework has been tested with solar energy companies, it can be applied to other business models in different sectors.

Keywords

Life cycle assessment (LCA); solar photovoltaics; circular economy; environmental sustainability; renewable energy; Africa

Highlights

- A new framework for quantifying environmental impacts of business models
- Framework includes LCA, business model innovation & participatory decision making
- First life cycle assessment of key solar energy business models in Africa
- Application quantifies potential of circular economy to increase sustainability
- Circular business models decrease most environmental impacts by 7%-73%

4. 1. Introduction

Circular economy (CE) is increasingly being accepted by policymakers as a development paradigm that has the potential to lead to environmental, social, and economic benefits (Halog and Anieke, 2021; Lüdeke-Freund et al., 2018; Preston et al., 2019). CE decouples value creation from resource consumption by minimising the use of resources, reducing waste and emissions (EEA, 2016; Geissdoerfer et al., 2017). Business models are the main drivers of transitioning to CE (Ellen MacArthur Foundation, 2015), therefore, companies play an important role in mitigating environmental impacts of production and consumption.

Traditional business models typically comprise interconnected elements that are designed to create goods and services that meet customers' needs for financial gain (Osterwalder and Pigneur, 2010). Circular business models integrate CE principles into their elements to minimise resource consumption, waste, and emissions associated with companies and their value network (Bocken et al., 2016). The main difference between traditional and circular business models is in the supply chain, the latter being focused on narrowing, slowing, and closing energy and material loops (Geissdoerfer et al., 2018). The feasibility of CE and circular business models must be evaluated against trade-offs and emerging conflicts of transitioning from a linear economy (Corvellec et al., 2021). For example, factors such as labour practices, equity, biophysical limits, rebound effects, and economic constraints are often overlooked (ibid).

There are several requirements to be met to facilitate the CE transition in incumbent companies. First, business model innovation must be performed alongside technological and social innovation (i.e., products, services, and partnerships that create new solutions to societal needs) (EEA, 2021). To this end, companies can transition from traditional to sustainable (and potentially more circular) business models by modifying their approach to value creation and delivery. Sustainable business models contribute to sustainable development by integrating environmental, social, and economic aspects in the creation of customer value while mitigating unwanted negative impacts (Lüdeke-Freund, 2010; Schaltegger et al., 2012; Stubbs and Cocklin, 2008). Circular business models are types of sustainable business models whose sustainability performance is enhanced by narrowing, slowing, dematerialising, intensifying, and closing loops for the long-term through stakeholder engagement, and financial and non-financial benefits (Geissdoerfer et al., 2018).

Other sustainable business models (e.g., product-service systems) can also be adopted to substitute traditional business models provided they considerably improve the overall social, economic, and environmental sustainability of companies throughout the life cycle of products and systems. Business model innovation must be performed to integrate principles of CE in the value propositions, for example, by providing repairs and maintenance to extend product lifetimes and slow resource loops (Bakker et al., 2014; Lewandowski, 2016). However, life extension is only beneficial if the use stage of a product is not the main hotspot of environmental impacts on a life cycle basis e.g., if a product is energy efficient (Loon et al., 2021). Business model innovation should also create new business models, and broaden the customer offering (Geissdoerfer et al., 2018).

Second, the transition requires the buy-in of stakeholders (Stubbs and Cocklin, 2008) at the outset of the innovation process to ensure that it is aligned with their priorities and has mutual opportunities for creating value (Oskam et al., 2020). Innovation within the boundaries of focal companies (e.g., within departments) and value network actors (e.g., manufacturers, developers, and recyclers) must occur concurrently to overcome barriers to current organisational arrangements (Velter et al., 2021). In contexts where business model innovation within an organisation depends on innovation in the value network, all actors must work towards a common goal of solving a joint problem (ibid; Tyl et al., 2015). Third, circular business models must have better environmental performance than traditional alternatives to make a case for substitution (Kjaer et al., 2016; Kjaer et al., 2018). This paper focuses on these three requirements to show how companies can evaluate and mitigate the environmental impacts of their business models. It should be noted that these requirements are not exhaustive but they are important for researchers aiming to generate the evidence needed to make a case for the potential of circular business models in focal companies.

Several frameworks for circular business models have been created to embed at least one of the three requirements to varying extents. These frameworks are for eco-innovations and the creation of new value (e.g., Bocken et al., 2014; Lüdeke-Freund, 2010), product-service systems (e.g., Brezet and Hemel, 2001; Maxwell et al., 2006), closed-loop systems (e.g., Chertow and Ehrenfeld, 2012; Rashid et al., 2013) sustainable production and consumption (e.g., Braungart et al., 2007; Tempelman et al., 2015), and conceptualising and implementing CE (Mendoza et al., 2017). Tools for evaluating environmental impacts such as life cycle assessment (LCA) have been included in a few frameworks (e.g., Böckin et al., 2022;

Maxwell et al., 2006; Manninen et al., 2018) while participatory approaches in business model innovation are considerably applied (e.g., Bocken et al., 2014).

Manninen et al. (2018) point out the growing interest in circular business models while their environmental evaluation remains underresearched. Sustainable business models arguably have a better environmental performance than traditional ones (Barquet et al., 2016; Mont, 2002). However, there are uncertainties about the extent and magnitude of their environmental sustainability (Tukker, 2015). Therefore, it is necessary to evaluate their environmental impacts to ascertain their potential to substitute traditional business models (product-centered e.g., sale of solar home systems) and under what conditions environmental benefits are achieved. Several frameworks have been created to include environmental assessment as part of the process of designing circular business models (e.g., Mendoza et al., 2017). However, the number of studies that quantify the environmental impacts of business models is still low because many studies tend to restrict the environmental assessments to qualitative analyses (Bocken et al., 2018; Lindahl et al., 2014).

This paper calls for an alternative perspective on the analysis of traditional business models adopted by companies. The consequences of adopting these business models and how they compare with their alternatives (e.g., those of CE) should always be considered in such analyses (Kjaer et al., 2016). To this end, the first objective of this paper is to create a comprehensive new framework for analysing the environmental impacts of business models (EBuM framework). The EBuM framework integrates business model innovation, LCA, and participatory decision-making to evaluate the environmental impacts of traditional and circular business models.

LCA is usually applied in the analysis of unit processes of products and systems throughout their lifetime. Business models are the means for creating and delivering products and systems to customers or end-users. There are different types of business models designed for each stage of a product's or system's life cycle. Therefore, business models provide a useful lens for evaluating the effect of company resources, activities, partnerships, customer preferences, and financial aspects on environmental impacts. Finally, stakeholders normally understand the business models of companies in detail and can provide the expertise needed to implement them. Therefore, stakeholder engagement in assessing the feasibility and approaches to addressing the environmental impacts of business models is crucial (Sommer, 2012). The EBuM framework combines the three elements (business model innovation, LCA, and participatory decision-making) to provide sequential steps of (i) quantifying the environmental impacts of traditional business models, (ii) incorporating stakeholders' input in hotspot analysis and identifying business models innovation strategies based on CE principles, (iii) quantifying the impacts of business model innovation and comparing them to the baseline case, and (iv) fine-tuning to determine under what conditions environmental benefits are realised.

The second objective of this study is to test the EBuM framework on solar energy companies in Kenya. Solar energy is the fastest-growing renewable energy in Africa in terms of installed capacity (REN 21, 2020) mainly due to technological advances and innovative business models. Kenya is selected for this analysis because it is among the fast-growing solar energy markets in Africa (IRENA, 2021) and a testing ground for new business models on the continent (IEA, 2017). To achieve the second objective, LCAs of four business models for solar photovoltaic (PV) systems are performed: rent-to-own for solar-home systems, pay-per-service unit for mini-grids, prosumer for commercial-scale PV, and engineering procurement and construction (EPC) with leasing for industrial-scale PV. Workshops with key stakeholders are conducted to discuss LCA results and business model innovation strategies that can mitigate the environmental impacts of incumbent business models. Thereafter, LCAs are conducted to examine the potential of the business model innovation in achieving better environmental outcomes.

As is the case in many countries in Africa, studies on solar energy business models in Kenya are widespread in academic literature (e.g., Lukuyu et al., 2021; Rolffs et al., 2016). Business models have extensively been scrutinised for their social and economic value. However, their environmental sustainability is sparsely documented, particularly, the negative impacts along the value chain (Mukoro et al., 2022). So far, previous studies quantified the life cycle impacts of a broad range of PV systems in Africa (e.g., Mukoro et al., 2021). However, they exclude the business models that implemented the systems yet the magnitude of environmental impacts of the PV systems is, to a considerable extent, determined by the business models' approach to creating and delivering value.

This paper furthers ongoing discussions on the environmental sustainability of renewable energy focusing on business model innovations. It creates the EBuM framework for examining the environmental impacts through the lens of business model innovation. The EBuM framework is flexible and can be replicated in other sectors or geographical contexts beyond Kenya's energy sector. It is designed to take into account stakeholders' concerns and priorities when evaluating environmental impacts and mitigation pathways. It also allows comparing traditional and new business models to draw conclusions on their environmental sustainability.

The rest of this paper is structured as follows. Section 4.2 describes the EBuM framework and how it is applied to case companies in Kenya. Section 4.3 presents the results and discussion of the study focusing on the LCA and workshop outcomes. Section 4.4 gives the conclusions. of the study by summarising the key findings and the limitations of the study.

4.2 Method

4.2.1 The EBuM framework

This study created a multi-step sequential EBuM framework to help companies perform LCAs of their business models and improve them through business model innovation (Figure 4). This framework has been adapted from the backcasting and eco-design (BECE) framework (Heyes et al., 2018; Mendoza et al., 2017; Mendoza et al., 2019a,b). The BECE framework comprises ten steps of envisioning, designing, and implementing new circular business models (Mendoza et al., 2017). It incorporates stakeholder engagement and employs LCA and eco-design tools in decision-making. The EBuM framework follows a similar approach of involving stakeholders in designing circular business models based on LCA outcomes. Unlike BECE, the main steps in EBuM are *identifying* the hotspots in incumbent business models, *evaluating* their consequences, *redesigning* business models, and *fine-tuning* (i.e., adjusting the input variables to test the robustness of the results).

The EBuM framework (Figure 4) brings together the business model canvas (Osterwalder and Pigneur, 2010), LCA (ISO 2006a,b), and participatory decision-making (Kaner et al., 2014). LCA is a standardised analytical tool that quantifies the environmental impacts of product systems while the business model canvas provides a structured approach to business model analysis and innovation. The canvas comprises nine blocks i.e., value proposition, key partnerships, key activities, customer segment, customer relationships, channels, cost structure, and revenue streams. It can help companies identify where they stand and devise suitable next steps to advance their business models (Chesbrough, 2007). LCA and the canvas can be paired to analyse and compare the impacts of traditional and circular business models. Such combinations are scarce in literature (Kjaer et al., 2016; Kjaer et al., 2018) but if used together, they create a comprehensive framework that can be applied across different business sectors. Participatory decision-making supports group thinking and multiple perspectives in problem-solving by taking advantage of the skills and experiences of participants (Kaner et al., 2014). In a company setting, participatory decision-making can be applied to shift from business-as-usual to inclusive decision-making that can be supported by stakeholders (ibid).

The analysis of business models is performed in two parts. The baseline case (steps 2 and 3 in Figure 4) is the first part and it represents the status quo while part two is the business model innovation scenarios that show the degree of change in environmental impacts brought about by transitioning to CE (steps 4 and 5). The analysis of financial aspects and customers' perception of business model innovation can be performed in steps 7 and 8 but they are outside the focus of the present study. A general description of employing the steps in conducting the LCA of any business model is described below. Section 4.2.2 explains how these steps have been applied to the case of solar companies in Kenya.

Identifying (steps 1 and 2): Stakeholder sampling and recruitment and business model baseline case (workshop 1).

The first step is to identify and recruit companies to participate in a given study. The rationale for engaging companies is to obtain data and draw from specialist knowledge of the sector. Once the companies are selected, they are introduced to the benefits of LCA analysis of business models, business model innovation, and case design. The first workshop brings together multiple stakeholders along the value chain (e.g., producers, distributors, developers, recyclers) to qualitatively analyse the incumbent business models towards a common goal. During the workshop, participants use the business model canvas to analyse the environmental sustainability of incumbent business models and evaluate the broader environmental priorities of the companies. The outcomes of the workshop are recorded by the research team and used as input for step 3.

Evaluating (step 3): LCA of incumbent business models

The research team administers questionnaires to collect foreground data on the life cycle inventory of products and services implemented in the key activities and key resource blocks of business models. The objective of the baseline case is to identify environmental hotspots in incumbent business models to inform step 4.

Redesigning (step 4): Business model innovation scenarios (workshop 2)

The second workshop aims to qualitatively analyse the outputs of step 3 i.e., hotspots and drivers of environmental impacts in the incumbent business models. The participants discuss the findings, propose, and evaluate improvements to their business models. The improvements can occur at four levels: (i) adjustments of a few business model elements excluding value propositions; (ii) adoption of new products or services and modifying customer aspects; (iii) simultaneously improving most elements of the business model; and (iv) redesigning the business model by adopting new value propositions (Mitchell and Coles, 2003, 2004; Schaltegger et al., 2011).

Fine-tuning (steps 5 and 6): LCA of the business model innovation scenarios and validation

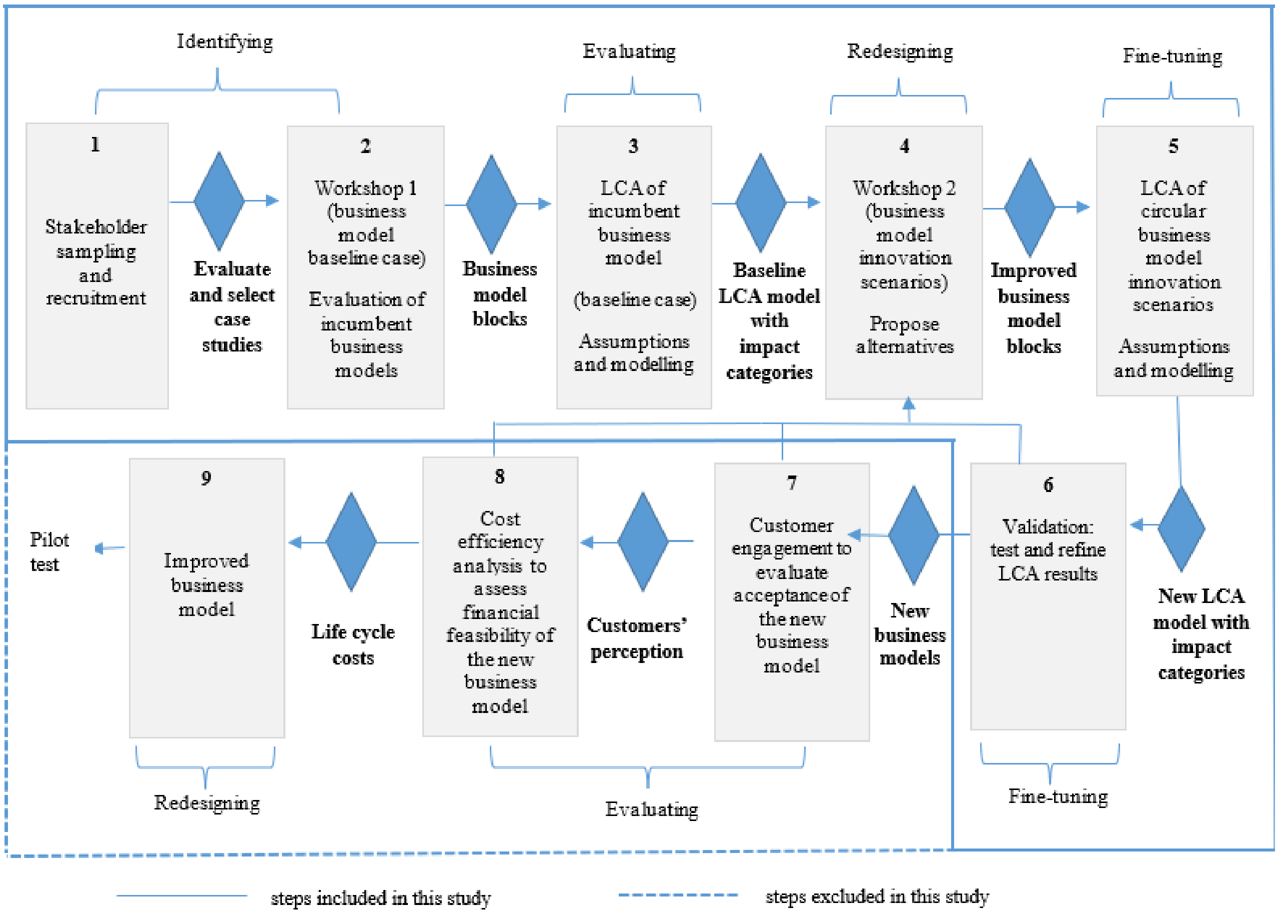
In step 5, the environmental impacts of the previously defined business model innovation scenarios (step 4) are evaluated using LCA. The material and energy inputs in the business model innovation scenarios are adjusted to reach an optimal amount of inputs that mitigate the impacts and allow for comparisons with the baseline case. The LCA results show to what extent the impacts change with narrowing, slowing, and closing resource loops relative to the baseline case. Validation (step 6) is done to ensure that the business model innovation scenarios have lower environmental impacts compared to the baseline. The circular business model innovation approach can be iterated in repeated cycles to test the sensitivity of the LCA results in the business model innovation scenario and review them with stakeholders.

Evaluating (steps 7 and 8): Customer engagement and cost-efficiency analysis

Stakeholders assess the feasibility of implementing the business model innovation outcomes of steps 4 and 5. Feasibility assessments are done to ascertain customers' reception and willingness to pay for the new value propositions and align the circular business models to consumer needs. A cost-efficiency analysis is performed to assess the viability of implementing the outcomes of step 5 using the least resources. The focus of this study is the environmental sustainability of business models, therefore, steps 7 and 8 are not tested because they are outside the scope. The social and economic dimensions of business models are extensively researched in literature while environmental issues are not well understood (e.g., Mukoro et al., 2022). Thus, this study focuses on environmental aspects to address the gap in the literature. It should be noted that social and financial considerations determine to what extent the recommendations for mitigating environmental impacts (steps 1 to 6) are applied or feasible. For example, if customers have a low willingness to adopt new value propositions or if mitigating environmental impacts is not cost-effective, companies will propose additional value propositions (step 4), making the process iterative.

Redesigning (step 9): improved business model

The company integrates social, economic, and environmental innovations to create a CE business model. The pilot business model should be tested under controlled conditions to determine what works, fails, and why before a full rollout in the market (Jørgensen and Pedersen, 2018). The focus of this study is the environmental dimension of business models, therefore, step 9 is not tested.



PV- photovoltaic; LCA- life cycle assessment; CE- circular economy

Figure 4: Research design for performing environmental analysis of business models: the EBuM framework

4.2.2 Application of the EBuM framework to the solar sector in Kenya

This study followed the sequential steps in section 4.2.1 and Figure 4 to collect data from the participating solar energy companies. This section specifically describes the types of data collected rather than how the steps were applied.

4.2.2. Overview of the companies

The first step (step 1) of the study was to identify solar energy companies in Kenya through a web search. Twenty companies were identified as ideal for engagement based on their business models and invited to participate in the study. Five companies expressed interest to take part in the research but only three were selected for engagement by eliminating duplication i.e., similar business models. The selected companies were distributors of solar PV technologies, developers, and system operators. The business models of these companies were representative of Kenya's on-grid and off-grid markets and can be a lens for understanding business models as drivers and mitigators of environmental impacts. The selection of several case companies was pivotal for this study because it allowed for comparisons, replication, generalisation and provides robust evidence for building an emerging theory founded on varied data sources (Eisenhardt and Graebner, 2007; Yin, 1994).

4.2.2.1 Workshops: business model analysis

Two separate workshops (steps 2 and 4 in Figure 4) were conducted and facilitated by the research team in each company. Participants comprised company staff i.e., engineers, business development analysts, and customer relations personnel. In the first workshop (step 2), the participants applied the business model canvas to discuss the elements of business models as summarised below. Participants also discussed to what extent the companies' incumbent business models were designed for environmental sustainability. The life cycle inventory questionnaire was administered during the first workshop to collect foreground data. Life cycle cost analysis was beyond the scope of this study therefore data on financial aspects of the business models were not collected.

- Value proposition: functions of bespoke solar energy solutions that meet customers' needs, approach to value creation, and its strengths;
- Supply-side: key partnerships e.g., with manufacturers, recyclers, and service providers; description of key resources e.g., solar PV systems, performance and lifetime of the systems, the volume of water used to wash panels, and frequency of cleaning; key activities e.g., distribution of solar PV systems, installation, operation and maintenance, take-back; and
- Demand-side: the use of either the PV systems or their function to meet customer needs.

During the second workshop, participants discussed these elements from a business model innovation perspective as described in step 4.

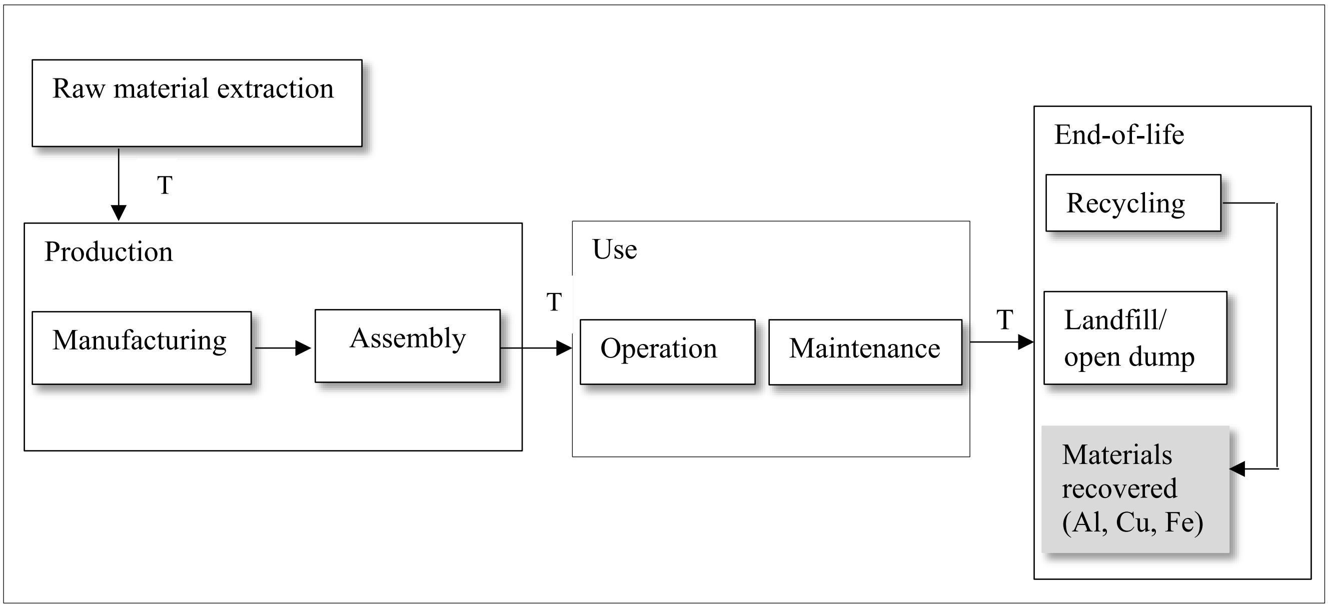
4.2.2.2 LCA process

LCAs were developed as part of steps 3 and 5. This study followed the LCA guidelines ISO 14040/14044 (ISO 2006 a,b), using SimaPro v9.0 (Pre Consultants, 2019) for modelling.

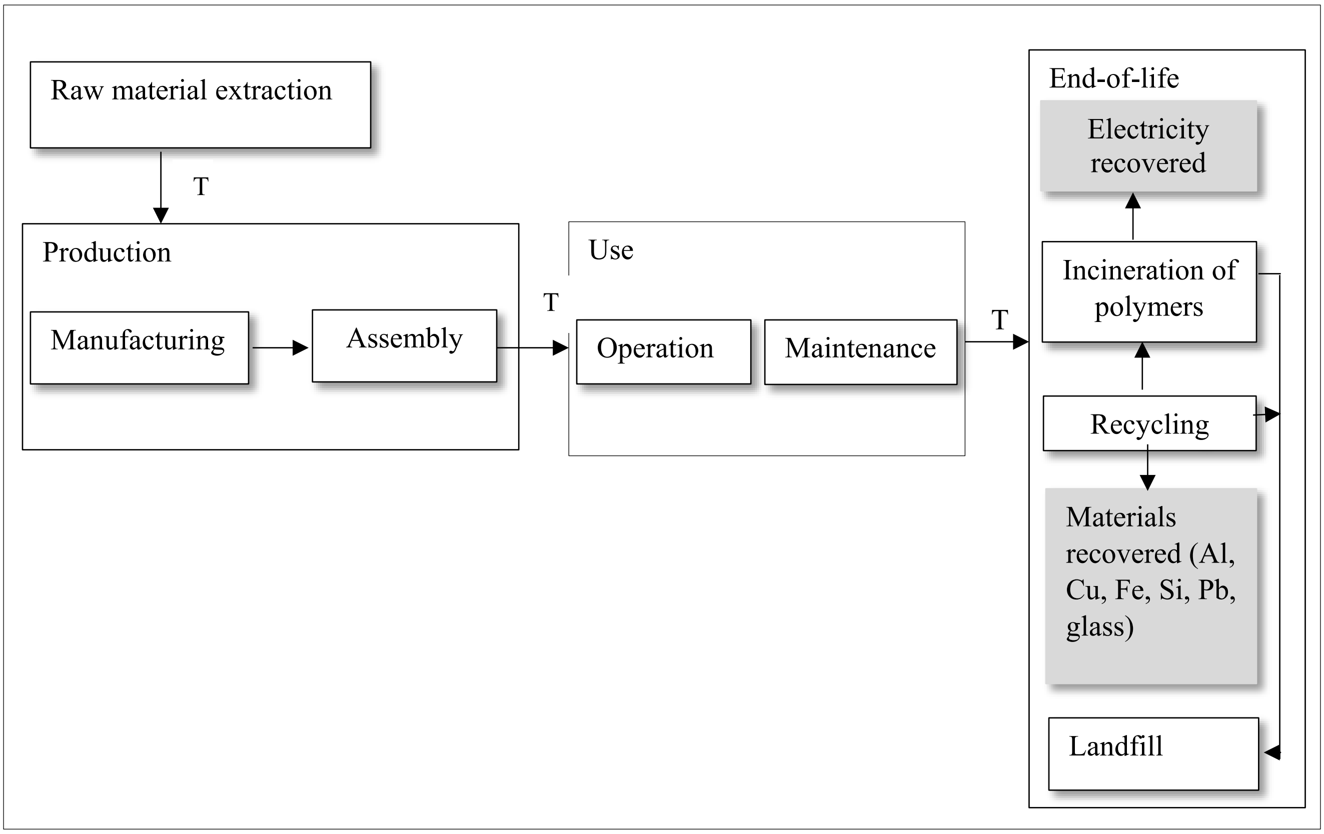
4.2.2.3 Goal and scope

The goal of this study was to evaluate the life cycle environmental impacts of generating electricity from a solar home system, a solar mini-grid, commercial-and-industrial-scale PV systems under the baseline and business model innovation scenarios. The intended use of the LCAs is hotspot identification in the baseline case and improvement potential in the business model innovation scenarios to allow for comparisons. The functional unit was the generation of 1 kWh of electricity from the solar PV systems throughout their lifetime. In the baseline case, the lifetime was 20 years for the solar home system and 25 years for the other PV systems while in the business model innovation scenarios, lifetimes of 25 and 40 years (NREL, nd) were assumed respectively, to maximise their useful life.

The scope of this study is cradle to grave (i.e., raw material extraction, manufacturing, transport, installation, use, and end-of-life). Figure 5 shows the processes included in the system boundary in the baseline (a) and business model innovation (b) cases.



(a)



(b)

Figure 5: System boundary for the baseline (a) and business model innovation (b) cases

In both cases, all the burden is allocated to the material's initial life. During the recycling process, the system bears the burden of recycling and is credited for the avoided production of virgin materials equivalent to the quantity of recycled materials. A 'net-scrap' approach is used whereby the fraction of scrap at production is subtracted from scrap at the end-of-life to get either net-scrap surplus or deficit (Bergsma and Sevenster, 2013; Gallego-Schmid et al., 2018; Gallego-Schmid et al., 2016).

4.2.2.3.2 Life cycle inventory

Foreground data were obtained from the companies as shown in Table A6 to Table A9 in SI, and background data from Ecoinvent v3.5 (Ecoinvent, 2018).

a) Raw material extraction and manufacturing

The production of multicrystalline solar panels, inverters, mounting structures, components of electric installation, and lead-acid batteries was modelled using Ecoinvent datasets for the rest of the world and adapted to the production process in China. The data were also adapted to the specific size of systems distributed, installed, or operated by the companies participating in this study. Data for manufacturing lead-acid batteries were missing in Ecoinvent, therefore, were obtained from Spanos et al. (2015) and Sullivan and Gaines (2012) (SI Table A 10). The recycled content of the lead-acid battery assumed was 70% lead and 100% for copper and polypropylene (Spanos et al., 2015).

b) Transport

The transport assumptions for this study are as follows: (i) components were transported by a 16 to 32 t Euro 3 truck over 150 km from the factory to a port in China, (ii) shipped to Kenya over 12223.2 km by a transoceanic freight ship, and (iii) transported to the installation site by Euro 3 truck over 816 km.

c) Use

Data on system availability, the average annual energy yield, and water consumption were obtained from the companies for the baseline case (Table A6 to Table A9 in SI) while the business model innovation scenarios assumed a lifetime of 25 to 40 years (NREL, nd). Monthly displacement of maintenance crew in a passenger bus over 5 km is assumed in all business models except rent-to-own for the solar home system at baseline. The company implementing the rent-to-own model only provided maintenance services within a two-year warranty period at baseline, hence, a 5 km distance is assumed during this period. In the business model innovation scenarios, all solar PV systems were assumed to be monitored remotely and maintained regularly.

d) End-of-life

There are two business-as-usual scenarios for handling e-waste in Kenya: (1) voluntary take back by companies for recycling in the formal sector and (2) informal collection and recycling (Africa Clean Energy Technical Assistance Facility, 2019). This study modelled the baseline end-of-life scenarios to reflect the business-as-usual situation in Kenya's e-waste sector. This study assumed that the solar home system in the rent-to-own business model is disposed of in a dumpsite with no recycling in the baseline case due to the absence of collection centres and take-back services in the remote rural areas where the systems are commonly distributed. A distance of 5 km travelled in a passenger car from the customer to the disposal site was assumed in this study. For the other PV systems, this study assumed that 50% of aluminium, copper, and steel were recycled from the components of which 10% was lost due to recycling inefficiencies. The Africa Waste Management Outlook projects that recycling rates in Africa will be 50% by 2030 while the African Union projects 50% recycling by 2023 in most African cities (UNEP, 2018), hence the assumption. Residual wastes from the recovery process alongside materials like glass, plastic mix, concrete, etc. were disposed of in landfills. It should be noted that the waste categories of metals disposed of in dumpsites were missing in Ecoinvent. In this case, available datasets for landfilling specific metals were used e.g., aluminium disposal in a sanitary landfill.

In the business model innovation scenarios, companies adopt take-back schemes and deliver waste to recyclers. These scenarios assumed a hypothetical case by adapting the Full Recovery End of Life Photovoltaic (FRELP) recycling process for crystalline PV (Latunussa et al., 2016) due to its high material recovery rate and recycling efficiencies. The recycling efficiencies for silicon, glass, copper, and aluminium from solar panels in the FRELP process are given in Table A11 in SI. Data for recycling copper, steel, lead, and aluminium recovered from the balance of systems were obtained from the literature (Table A11). Non-recycled materials like polymers were assumed to be incinerated with electricity recovery and residual waste from all waste treatment processes disposed of in special material landfills. These end-of-life assumptions present the best-case scenarios found in literature and may not represent the existing case.

4.2.2.3.3 Life impact assessment

Eighteen impact categories are calculated using ReCiPe 2016 midpoint (Huijbregts et al., 2016) and the default hierarchist perspective model because it establishes a balance between managing environmental impacts and taking precautions to mitigate them (Schryver et al., 2011).

4.3 Results and discussion

In the following subsections, the findings are presented as follows: section 4.3.1 gives the outcomes of the workshops while section 4.3.2 presents the environmental impact assessment.

4.3.1 Workshop outcomes

Table 3 describes the solar PV systems implemented by each business model while Table 4 summarises the business blocks of the participating companies. Findings show that incumbent business models are CE-oriented only to a small extent. These business models operate in the procurement, distribution, and use stages of the value chain by directly supporting product service systems, product life extension, and indirectly recycling to varying extents. These business models present suitable cases to assess the potential of becoming more circular within and outside the boundaries of focal companies.

The value proposition mimics the functional unit in LCAs and denotes the function and output of the business models (Joyce and Paquin, 2016). The aggregated environmental impacts of the solar PV systems for each business model are expressed per kilowatt-hour (section 4.3.2*t*) and in a broad sense per value proposition. At baseline, the environmental focus for PSS business models (Table 4) was mainly for the use stage i.e., extending the lifetime and use of solar PV systems through maintenance. Unlike the PSS business models, the value proposition of the rent-to-own model (Table 4) is not designed for environmental sustainability beyond the distribution of clean energy technologies. Yet, the value propositions directly or indirectly affect all life cycle stages of their projects.

Table 3: Characteristics of solar PV systems in the sample, their application, and business models

	Rent-to-own: SHS	**Pay-per-service-unit: mini-grid**	**Prosumer: commercial-scale**	**Engineering Procurement and lease-to-own: industrial-scale**
Size	0.1 kWp	20 kWp	600 kWp	180 kWp
Current	DC	AC	AC	AC
Components	100 W multicrystalline silicon panel, l12V/100Ah PbA battery	265 W multicrystalline silicon panel, 48V/3000Ah PbA battery, 20 kWp and 13kWp solar and battery inverters, mounting structure, components of electric installation	250 W multicrystalline silicon, panel 17 kW inverters, mounting structure, components of electric installation	370 W multicrystalline silicon panel, 50 kW and 25 kW inverters, mounting structure, components of electric installation
Installation	Plug-and-play	Ground-mounted	Roof-mounted	Roof-mounted
Lifetime	Solar panel 20 years; battery 10 years replaced once	Solar panel 25 years; inverter 15 years replaced once; battery 10 years replaced twice; mounting structure 30 years not replaced; components of electric installation not replaced	Solar panel 25 years; inverter 15 years replaced once; mounting structure 30 years not replaced; components of electric installation	Solar panel 25 years; inverter 15 years replaced once; mounting structure 30 years not replaced; components of electric installation
Application	Off-grid	Off-grid	On-grid	Captive use

Uses	DC loads-	AC loads (low to moderate power consumption)	Feed electricity to the grid to power AC loads	AC loads during the day (low to high power consumption)

AC- alternating current; Ah- ampere-hour; DC- direct current; kW- kilowatt; kWp- kilowatt-peak; V- volt; W- watt

Table 4: Characteristics of the investigated solar PV business models at baseline

	Rent-to-own (SHS)	**Pay-per-service-unit (mini-grid)**	**Prosumer (commercial-scale)**	**EPC with lease-to-own (industrial-scale)**
Archetype	Cash sales and pay-as-you-go (Non-PSS)	PSS (results-oriented)	PSS (results-oriented)	PSS (product-oriented)
Value proposition	Customers rent and use SHS while paying the purchase price in fixed instalments. Ownership of the SHS is transferred to customers upon completion of payment. SHS generates electricity for up to 20 years. Storage batteries supply electricity at night.	The company constructs, owns, and operates solar mini-grids and supplies electricity to customers. Mini-grids generate electricity for 25 years. Storage batteries supply electricity at night.	The company constructs, owns, and operates solar PV systems installed on its premises. The solar PV system generates electricity for daytime use and supplies surplus to the grid for 25 years.	The company meets the cost of procuring and installing solar PV systems on the premises of clients. The clients use and pay for the system on a lease basis or the electricity on a PPA. The ownership of the system is transferred to the client at the end of the lease period for unlimited use. The systems provide captive daytime use for 25 years.
Key activities	Distribution and sale of SHS, no take-back at (disposal by end-user)	Installation, O&M, take-back (landfill & recycling)	Installation and O&M, take-back (landfill & recycling)	EPC with optional O&M, take-back (landfill & recycling)
Key resources	SHS	Mini-grid infrastrucutre	Commercial-scale PV system	Industrial-scale PV system
Key partnerships	Linear supply chain, financial partners	Linear supply chain, financial partners	Linear supply chain, financial partners	Linear supply chain, financial partners
Customer segments	Households and businesses in off-grid areas	Households, businesses, institutions	National grid	Industries
Customer relationships	Transactional & warranty, no take-back, the customer is responsible for end-life	Electricity supply, long-term, company is responsible for end-of-life	Electricity supply, long-term, company is responsible for end-of-life	Turnkey solutions, transactional or long-term, optional take-back, company or customer is responsible for end-of-life
Distribution Channels	Road and ship, retail	Road and ship, direct supply to end-user	Road and ship, direct-supply to customer	Road and ship, turnkey sales

Costs	CapEX, administrative costs	CapEX and OpEX	CapEX and OpEX	CapEX , OpEX optional
Revenue	Pay-as-you-go fees or outright purchase fees	Price per kWh	PPA price	EPC price, leasing and PPA price

CapEX- capital expenditure; EOL- end-of-life; EPC- Engineering Procurement and Construction; kWh-kilowatt-hour; OpEX- operating expenditure; O&M- operation and maintenance; PPA-Power Purchase Agreement; PSS- product service system; PV- photovoltaic; and SHS- Solar Home System.

Several approaches to modifying value propositions to be aligned with CE were discussed by participants during the second workshop (step 4 in Figure 4) to enhance resource efficiency and minimise emissions. The extent of integrating new “more circular” value propositions in individual business models depended on their value propositions at baseline. For example, the rent-to-own business model is more inclined to the linear-economy approach and, therefore, allows the integration of more circular aspects, unlike the pay-per-service unit business model, which is already closer to a CE approach. The following new value propositions were proposed by the companies during the second workshop to enhance environmental sustainability throughout the value chain:

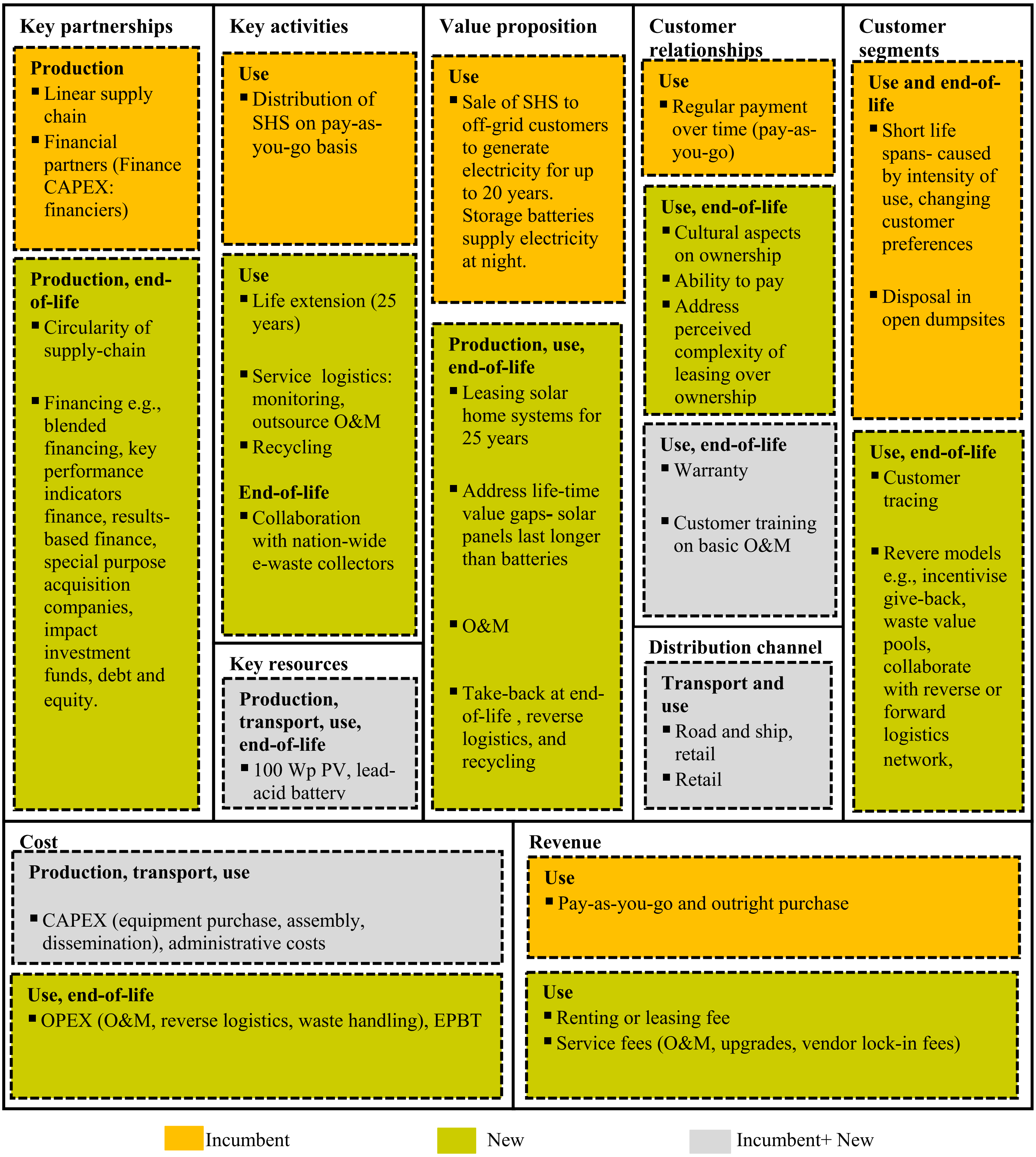
- Sharing platforms: a shift from the sale of products in incumbent rent-to-own and EPC-lease-to-own business models to leasing the systems. The companies maintain ownership of the PV systems.
- Product optimisation and value-added services: digitalisation, monitoring, upgrades, and maintenance to optimise lifetime in all business models;
- Resource value and circular supply chains: strategic partnerships for take-back and high recycling rates to displace the use of primary materials in manufacturing processes. Residual non-recyclable waste is incinerated with energy recovery or disposed of in special material landfills.

Figures 6- 9 show the amendments to the incumbent rent-to-own business model while Figures 10- 13 illustrate the innovation pathways that are essential to transitioning to CE. The value propositions of the four business models have a direct bearing on the lifetime energy yield of each solar PV system and subsequently, environmental impacts. Extending the useful life of the solar PV systems from 20-25 years at baseline (Table 3) to 25-40 years in the business model innovation scenario results in an overall reduction in aggregated environmental impacts as discussed in section 4.3.2. Low annual degradation rates of less than 1% make it possible for solar panels to generate a substantial amount of electricity after 25 years (Jordan and Kurtz, 2012). The companies anticipate a drop in the power output of their PV systems beyond 25 years considering a degradation rate of 0.7% per year but expect them to still perform optimally for low voltage uses. Other than the solar home system, the larger PV systems are licensed by the regulator to operate commercially for 25 years. Accordingly, the value propositions in the business model innovation scenario can potentially change after the 25th year.

When value propositions change considerably due to business model innovation e.g., shifting from product sales to leasing, their adoption will depend on the companies' ability to meet baseline customer needs. Customer engagement can be conducted in future work to evaluate how the adoption of new value propositions is affected by the end-users ability-to-pay and compatibility with lifestyle and cultural practices. Trying out the business model innovation pathways in a controlled test ground is necessary for companies to gauge market performance without major disruptions to baseline activities (Chesbrough, 2010). The tests can evaluate the customer needs, additional activities, key resources, new partnerships, and financial requirements of substituting incumbent business models. Adopting sustainable business models should also consider the facilities or infrastructure that need to be introduced or extended to create and deliver value (Amaya et al., 2014).

Factors such as consumer needs, stakeholders' expectations, and the availability of technical skills (Buysse and Verbeke, 2003; Lowitzsch, 2019) also determine the extent to which the companies will innovate their business models. According to Gambardella and McGahan (2010), incumbent companies can readily adopt viable business model innovations to earn or diversify revenue. The business model substitutes must demonstrate a positive contribution to companies' economic outcomes (e.g., risk reduction, customer retention, profit, and market development) and competitive advantage to prove a business case for environmental sustainability (Schaltegger et al., 2011; Schaltegger and Synnestvedt, 2002). Cost-efficiency assessment of business model innovation and customer engagement was outside the scope of this study. However, in future research, it would be essential to evaluate the economic viability of business model innovation. Ideally, the cost of business model innovation must be kept down by introducing new value propositions incrementally rather than radically, to avoid driving up costs and causing market segregation (Jørgensen and Pedersen, 2018). For the existing customer base, incremental changes allow for monitoring, evaluation, and fine-tuning to reduce the risk of loss of market share while maintaining profitability.

Rent-to-own business model canvas (solar home system)



Key partnerships

🟧 **Production**
- Linear supply chain
- Financial partners (Finance CAPEX: financiers)

🟩 **Production, end-of-life**
- Circularity of supply-chain
- Financing e.g., blended financing, key performance indicators finance, results-based finance, special purpose acquisition companies, impact investment funds, debt and equity.

Key activities

🟧 **Use**
- Distribution of SHS on pay-as-you-go basis

🟩 **Use**
- Life extension (25 years)
- Service logistics: monitoring, outsource O&M
- Recycling

End-of-life
- Collaboration with nation-wide e-waste collectors

Key resources

⬜ **Production, transport, use, end-of-life**
- 100 Wp PV, lead-acid battery

Value proposition

🟧 **Use**
- Sale of SHS to off-grid customers to generate electricity for up to 20 years. Storage batteries supply electricity at night.

🟩 **Production, use, end-of-life**
- Leasing solar home systems for 25 years
- Address life-time value gaps- solar panels last longer than batteries
- O&M
- Take-back at end-of-life , reverse logistics, and recycling

Customer relationships

🟧 **Use**
- Regular payment over time (pay-as-you-go)

🟩 **Use, end-of-life**
- Cultural aspects on ownership
- Ability to pay
- Address perceived complexity of leasing over ownership

⬜ **Use, end-of-life**
- Warranty
- Customer training on basic O&M

Distribution channel

⬜ **Transport and use**
- Road and ship, retail
- Retail

Customer segments

🟧 **Use and end-of-life**
- Short life spans- caused by intensity of use, changing customer preferences
- Disposal in open dumpsites

🟩 **Use, end-of-life**
- Customer tracing
- Revere models e.g., incentivise give-back, waste value pools, collaborate with reverse or forward logistics network,

Cost

⬜ **Production, transport, use**
- CAPEX (equipment purchase, assembly, dissemination), administrative costs

🟩 **Use, end-of-life**
- OPEX (O&M, reverse logistics, waste handling), EPBT

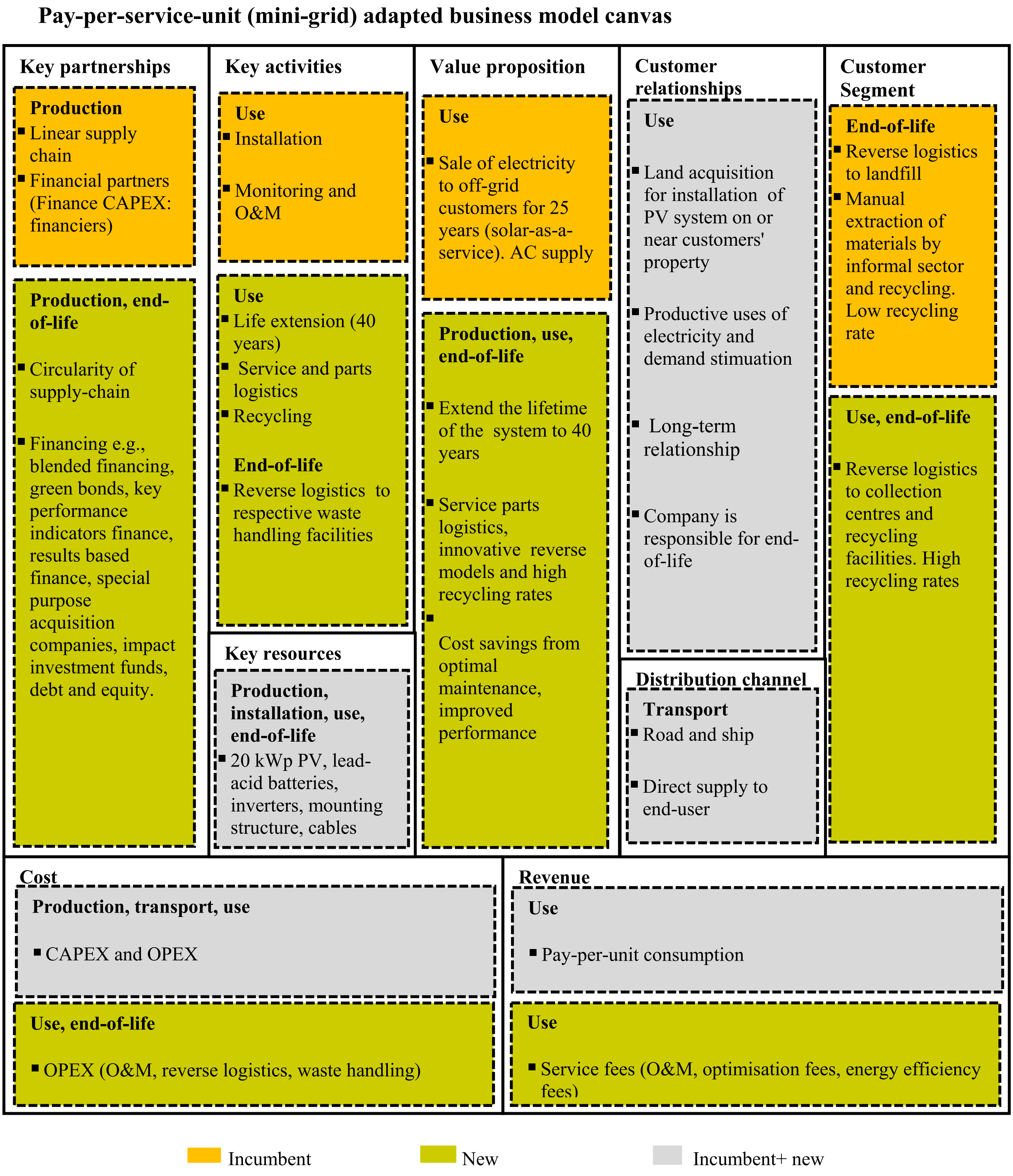
Revenue

🟧 **Use**
- Pay-as-you-go and outright purchase

🟩 **Use**
- Renting or leasing fee
- Service fees (O&M, upgrades, vendor lock-in fees)

🟧 Incumbent 🟩 New ⬜ Incumbent+ New

Figure 6: Baseline and business model innovation scenarios for rent-to-own business model. CAPEX-capital expenditure; DC- direct current; EPBT- energy payback time; O&M- operation and maintenance OPEX-operating expenditure; SHS- solar home system; Wp- watt-peak.



Pay-per-service-unit (mini-grid) adapted business model canvas

Key partnerships

🟧 **Production**
- Linear supply chain
- Financial partners (Finance CAPEX: financiers)

🟩 **Production, end-of-life**
- Circularity of supply-chain
- Financing e.g., blended financing, green bonds, key performance indicators finance, results based finance, special purpose acquisition companies, impact investment funds, debt and equity.

Key activities

🟧 **Use**
- Installation
- Monitoring and O&M

🟩 **Use**
- Life extension (40 years)
- Service and parts logistics
- Recycling

End-of-life
- Reverse logistics to respective waste handling facilities

Key resources

⬜ **Production, installation, use, end-of-life**
- 20 kWp PV, lead-acid batteries, inverters, mounting structure, cables

Value proposition

🟧 **Use**
- Sale of electricity to off-grid customers for 25 years (solar-as-a-service). AC supply

🟩 **Production, use, end-of-life**
- Extend the lifetime of the system to 40 years
- Service parts logistics, innovative reverse models and high recycling rates
- Cost savings from optimal maintenance, improved performance

Customer relationships

⬜ **Use**
- Land acquisition for installation of PV system on or near customers' property
- Productive uses of electricity and demand stimuation
- Long-term relationship
- Company is responsible for end-of-life

Distribution channel

⬜ **Transport**
- Road and ship
- Direct supply to end-user

Customer Segment

🟧 **End-of-life**
- Reverse logistics to landfill
- Manual extraction of materials by informal sector and recycling. Low recycling rate

🟩 **Use, end-of-life**
- Reverse logistics to collection centres and recycling facilities. High recycling rates

Cost

⬜ **Production, transport, use**
- CAPEX and OPEX

🟩 **Use, end-of-life**
- OPEX (O&M, reverse logistics, waste handling)

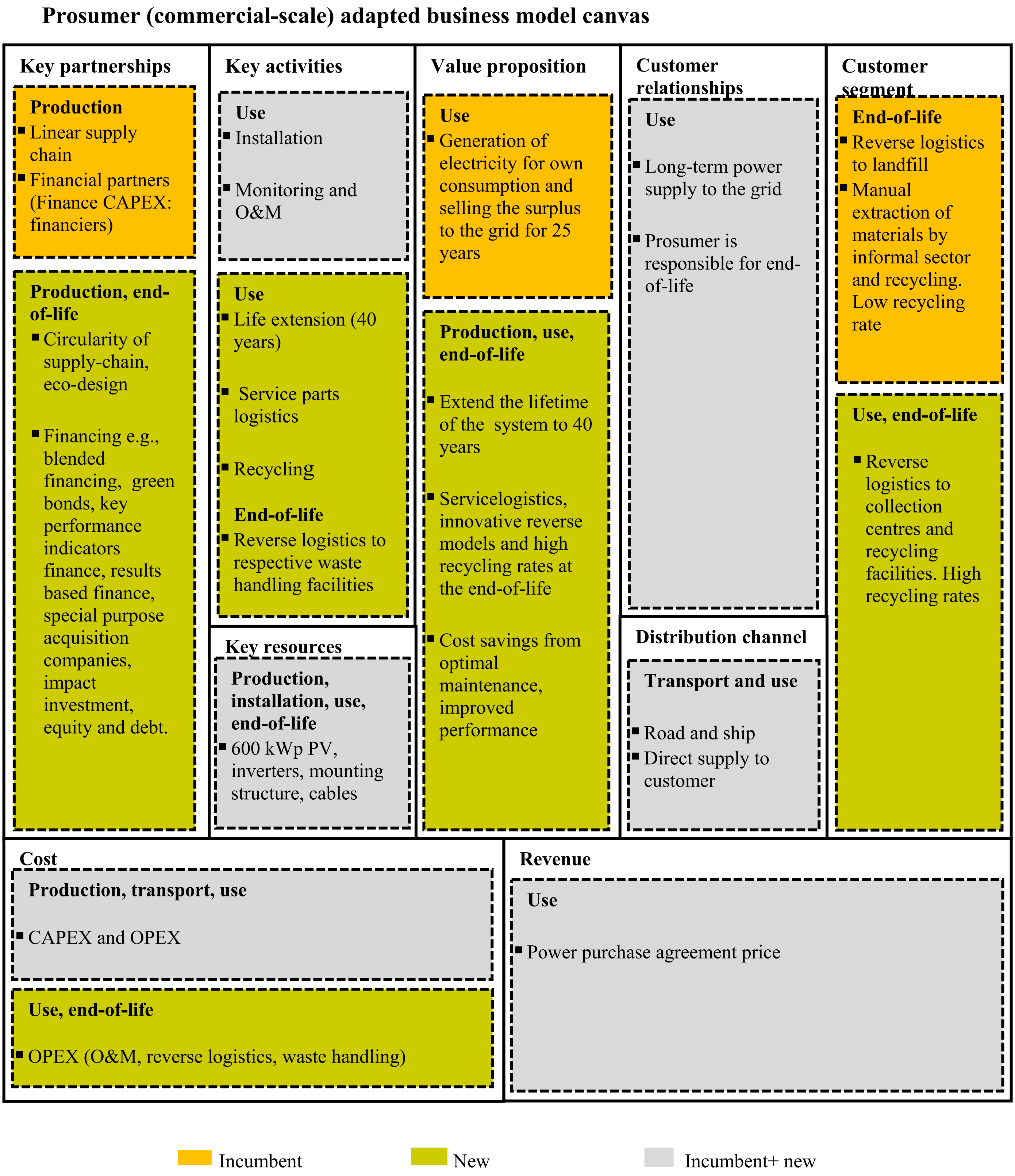
Revenue

⬜ **Use**
- Pay-per-unit consumption

🟩 **Use**
- Service fees (O&M, optimisation fees, energy efficiency fees)

🟧 Incumbent 🟩 New ⬜ Incumbent+ new

Figure 7: Baseline and business model innovation scenarios for pay-per-service business model. AC- Alternating current; CAPEX- capital expenditure; O&M- operation and maintenance; OPEX-operation expenditure; kWp- kilowatt peak.



Prosumer (commercial-scale) adapted business model canvas

Key partnerships

🟧 **Production**
- Linear supply chain
- Financial partners (Finance CAPEX: financiers)

🟨 **Production, end-of-life**
- Circularity of supply-chain, eco-design
- Financing e.g., blended financing, green bonds, key performance indicators finance, results based finance, special purpose acquisition companies, impact investment, equity and debt.

Key activities

⬜ **Use**
- Installation
- Monitoring and O&M

🟨 **Use**
- Life extension (40 years)
- Service parts logistics
- Recycling

End-of-life
- Reverse logistics to respective waste handling facilities

Key resources

⬜ **Production, installation, use, end-of-life**
- 600 kWp PV, inverters, mounting structure, cables

Value proposition

🟧 **Use**
- Generation of electricity for own consumption and selling the surplus to the grid for 25 years

🟨 **Production, use, end-of-life**
- Extend the lifetime of the system to 40 years
- Servicelogistics, innovative reverse models and high recycling rates at the end-of-life
- Cost savings from optimal maintenance, improved performance

Customer relationships

⬜ **Use**
- Long-term power supply to the grid
- Prosumer is responsible for end-of-life

Distribution channel

⬜ **Transport and use**
- Road and ship
- Direct supply to customer

Customer segment

🟧 **End-of-life**
- Reverse logistics to landfill
- Manual extraction of materials by informal sector and recycling. Low recycling rate

🟨 **Use, end-of-life**
- Reverse logistics to collection centres and recycling facilities. High recycling rates

Cost

⬜ **Production, transport, use**
- CAPEX and OPEX

🟨 **Use, end-of-life**
- OPEX (O&M, reverse logistics, waste handling)

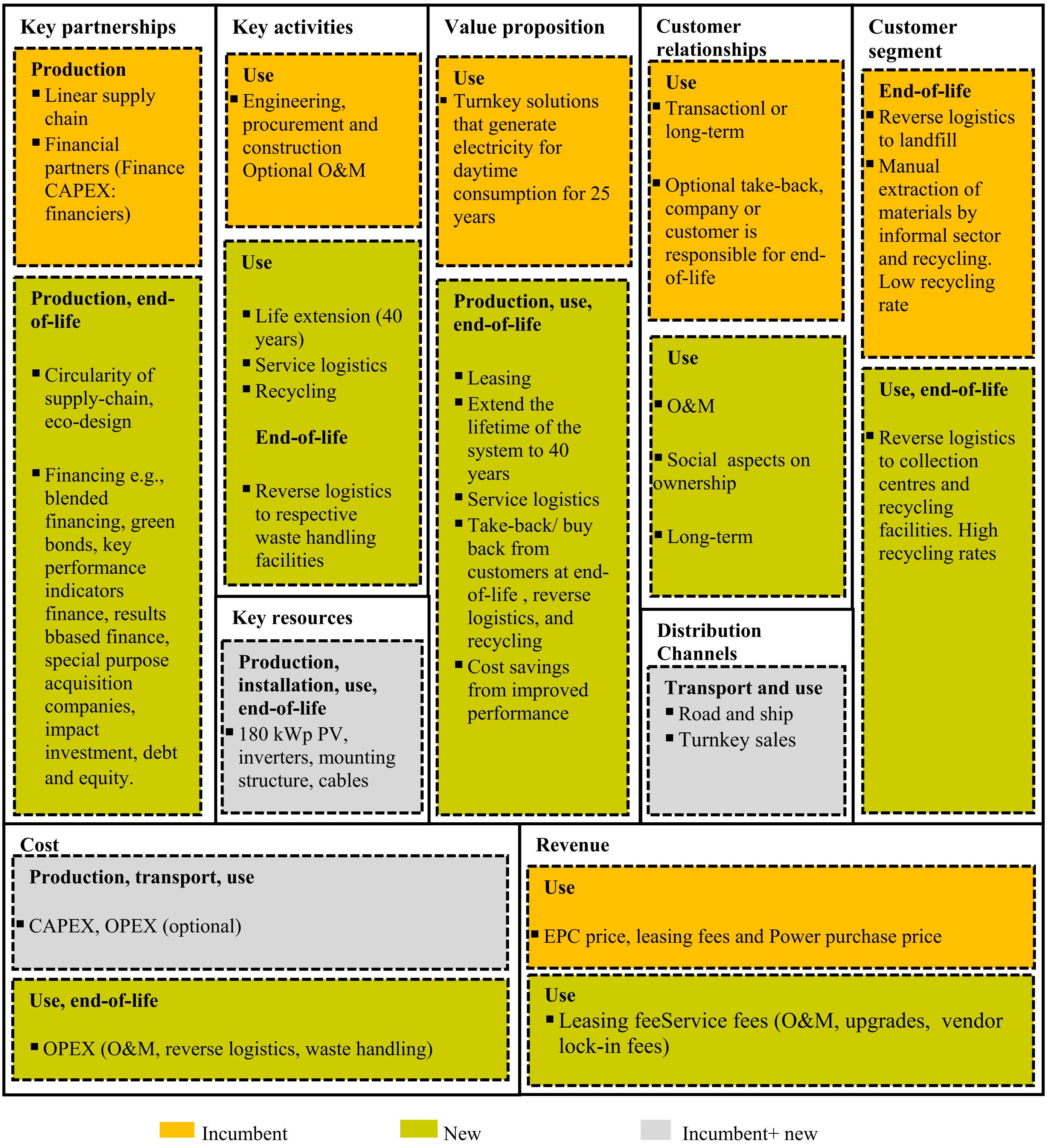
Revenue

⬜ **Use**
- Power purchase agreement price

🟧 Incumbent 🟨 New ⬜ Incumbent+ new

Figure 8: Baseline and business model innovation scenarios for prosumer business model. AC- Alternating current; CAPEX- capital expenditure; O&M- operation and maintenance; OPEX-operation expenditure; SHS-solar home system; kWp- kilowatt peak.

Engineering Procurement and Construction (industrial-scale) adapted business model canvas



Key partnerships

Production
- Linear supply chain
- Financial partners (Finance CAPEX: financiers)

Production, end-of-life
- Circularity of supply-chain, eco-design
- Financing e.g., blended financing, green bonds, key performance indicators finance, results bbased finance, special purpose acquisition companies, impact investment, debt and equity.

Key activities

Use
- Engineering, procurement and construction Optional O&M

Use
- Life extension (40 years)
- Service logistics
- Recycling

End-of-life
- Reverse logistics to respective waste handling facilities

Key resources

Production, installation, use, end-of-life
- 180 kWp PV, inverters, mounting structure, cables

Value proposition

Use
- Turnkey solutions that generate electricity for daytime consumption for 25 years

Production, use, end-of-life
- Leasing
- Extend the lifetime of the system to 40 years
- Service logistics
- Take-back/ buy back from customers at end-of-life , reverse logistics, and recycling
- Cost savings from improved performance

Customer relationships

Use
- Transactionl or long-term
- Optional take-back, company or customer is responsible for end-of-life

Use
- O&M
- Social aspects on ownership
- Long-term

Distribution Channels

Transport and use
- Road and ship
- Turnkey sales

Customer segment

End-of-life
- Reverse logistics to landfill
- Manual extraction of materials by informal sector and recycling. Low recycling rate

Use, end-of-life
- Reverse logistics to collection centres and recycling facilities. High recycling rates

Cost

Production, transport, use
- CAPEX, OPEX (optional)

Use, end-of-life
- OPEX (O&M, reverse logistics, waste handling)

Revenue

Use
- EPC price, leasing fees and Power purchase price

Use
- Leasing feeService fees (O&M, upgrades, vendor lock-in fees)

🟧 Incumbent 🟨 New ⬜ Incumbent+ new

Figure 9: Baseline and business model innovation scenarios for the Engineering Procurement and Construction business model. AC- Alternating current; CAPEX- capital expenditure; O&M- operation and maintenance; OPEX-operation expenditure; SHS- solar home system; kWp- kilowatt peak.

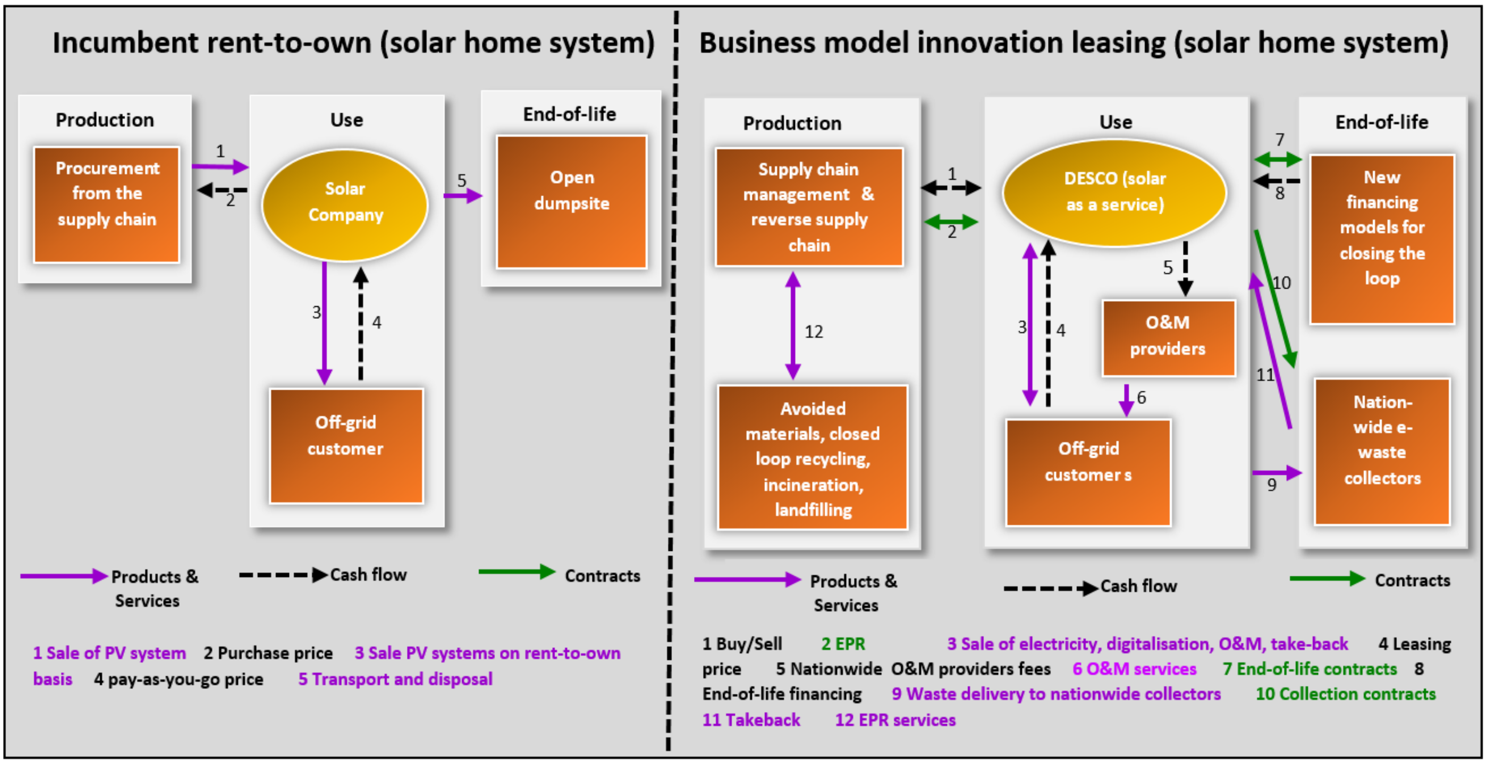


Figure 10: Business model innovation pathway for the rent-to-own business model. DESCO - distributed energy service company; EPR - extended producer responsibility; O&M - operation and maintenance; PV - photovoltaic.

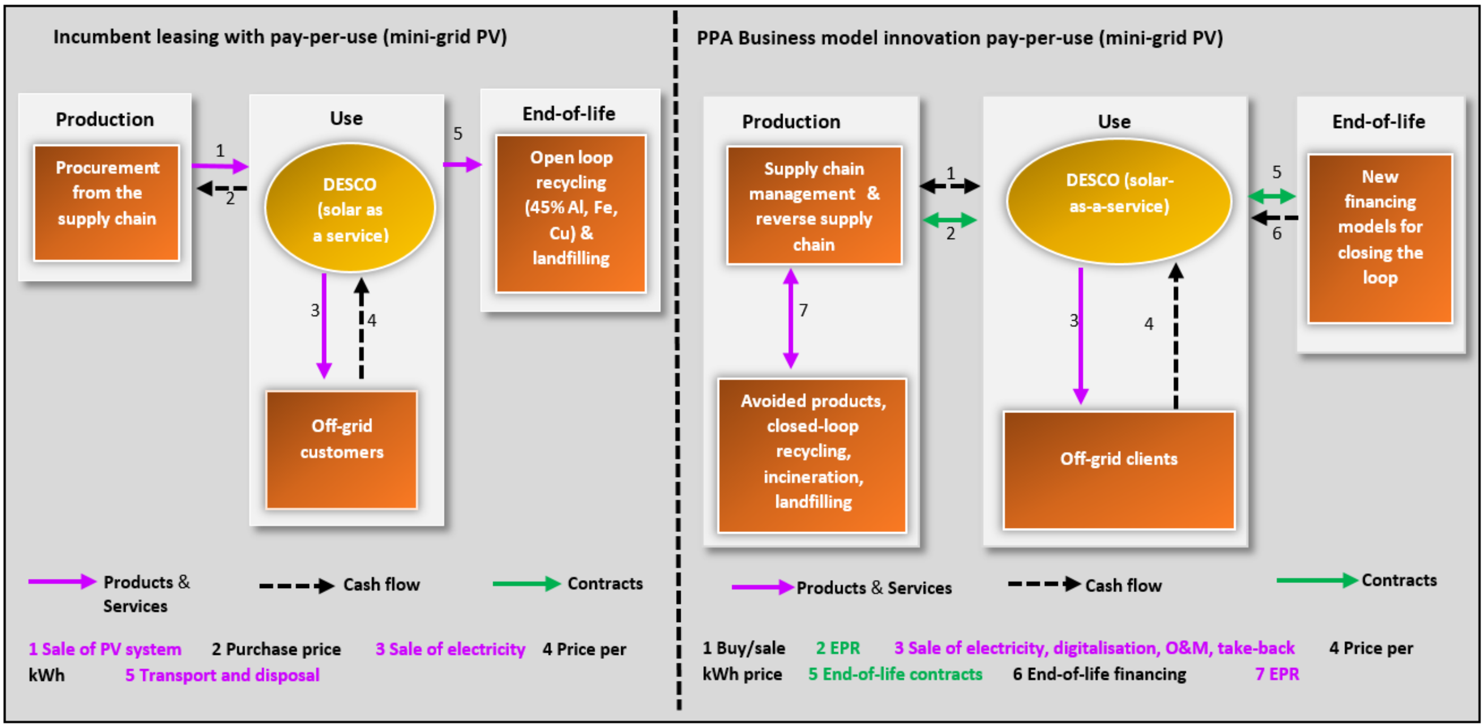


Figure 11: Business model innovation pathway for the pay-per-service business model. DESCO - distributed energy service company; EPR - extended producer responsibility; O&M - operation and maintenance; PV - photovoltaic.

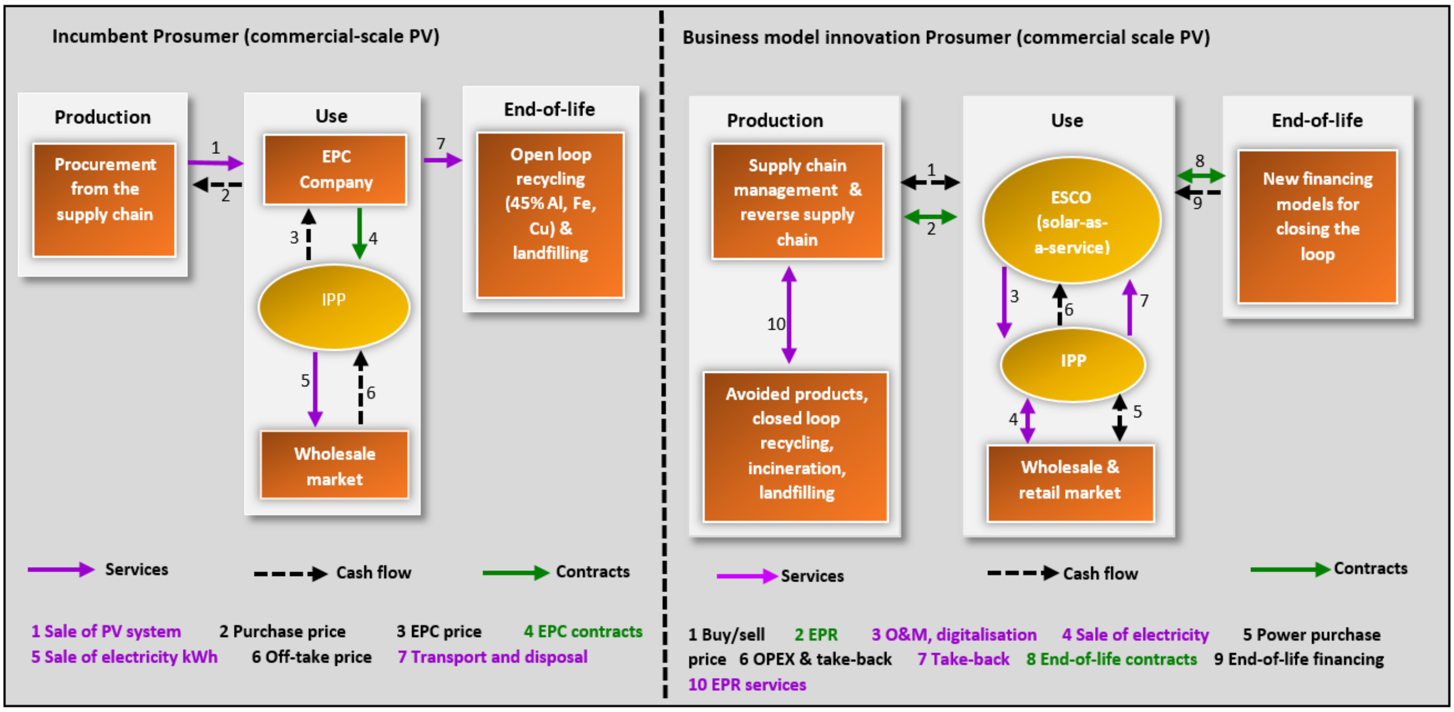


Figure 12: Business model innovation pathway for the prosumer business model. ESCO - distributed energy service company; EPR - extended producer responsibility; O&M - operation and maintenance; PV - photovoltaic.

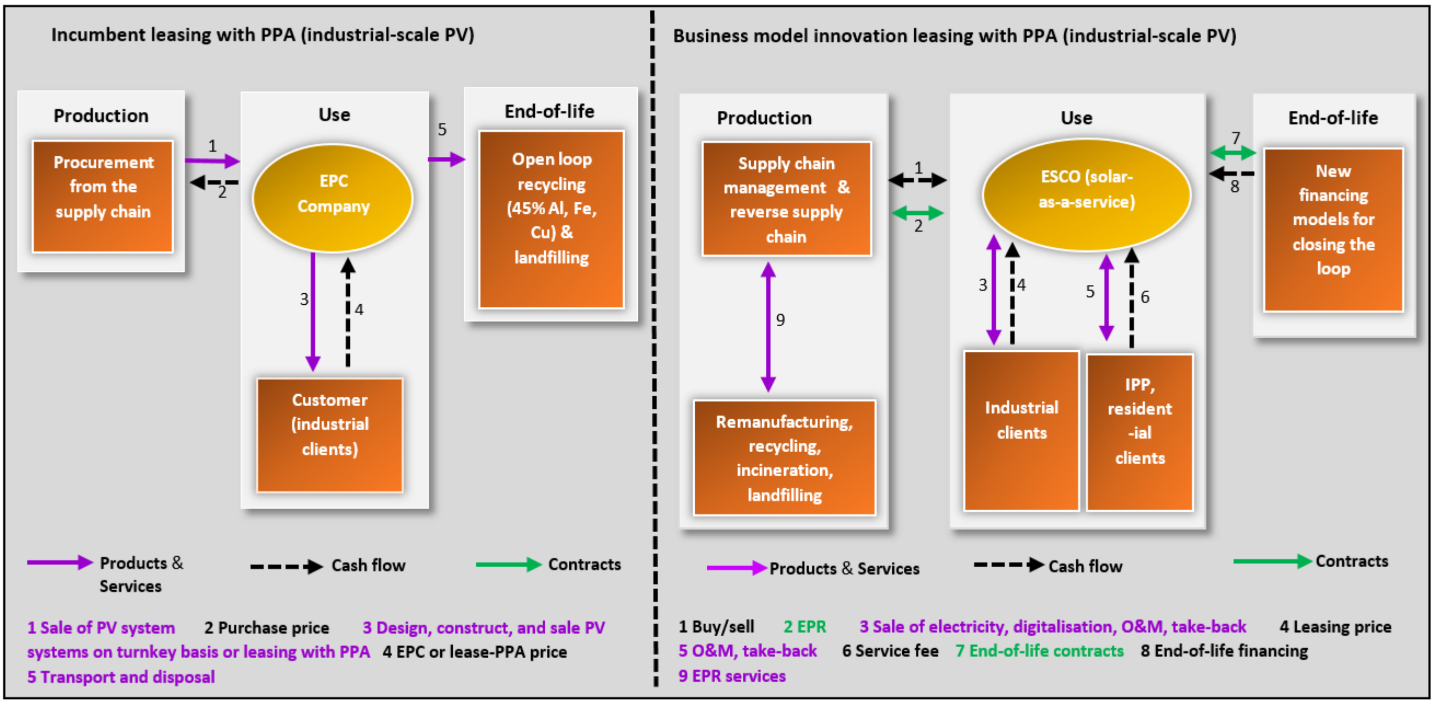


Figure 13: Business model innovation pathway for the Engineering Procurement and Construction business model. ESCO - distributed energy service company; EPR - extended producer responsibility; O&M - operation and maintenance; PV - photovoltaic.

4.3.2 Impact assessment

A combination of the new value propositions lowers environmental impacts in most categories (Figure 14) on the premise of embodied carbon, emissions savings, and resource efficiency. At baseline, recycling rates are low, therefore, negative environmental impacts shifts impacts of unrecycled materials upstream. In this case, the environmental burden is attributed to the incumbent business model. In the business model innovation scenarios, life extension and closed-looped recycling mainly reduce environmental impacts in the range shown in Figure 14. The results show that the avoided impacts of displacing incumbent value propositions are significant across most impact categories, hence the business model innovation scenarios have superior environmental performance. However, the rebound effects of the proposed value propositions have not been assessed in this study.

The solar PV systems and business models serve different functions considering their technology composition. Therefore, this study does not compare them on basis of environmental performance. Supply-side impacts of the business models directly stem from key partnerships with the supply chain, key resources (technology composition), and key activities in the value chain (life cycle stages). At baseline, the relationship between the energy companies and the supply chain is mainly transactional rather than collaborative. Key actors such as manufacturers, developers, and recyclers operate in isolation along the value chain resulting in burden-shifting. For example, a lack of partnerships for closed-looped recycling at baseline results in low recycling rates (50% copper, aluminium, and steel) and high metal depletion potential across all business models (Figure 14). Consequently, the upstream impacts from the extraction and production of primary materials are significant (Figure 14). In the business model innovation scenarios, the companies evaluated strategic partnerships for closing the loop. For example extended producer responsibility or take-back agreements with the supply chain, existing service logistic networks, nationwide electronic waste collectors, and recyclers. Assuming high recycling rates (e.g., between 69% and 99% for PV) and avoided production of primary materials (see Table A11in SI) the business model innovation scenarios avoid significant environmental impacts across all impact categories as shown in Figure 14.

Transport impacts are negligible in all business models, except in the rent-to-own business model, where introducing new activities such as leasing with maintenance and take-back increased transport impacts by up to 7% in the business model innovation scenarios. Use stage impacts are also negligible in all business models and impact categories except for land-use impacts in ground-mounted systems and water depletion potential from washing solar panels. Transport emissions for maintenance are relatively small (less than 10% in the different impact categories) compared to other activities like production.

4. 3.2.1 Climate change potential (CCP)

CCP impacts are associated with the emission of CO_2 and CH_4 from the combustion of fossil fuels in upstream and downstream activities. In the incumbent business models' case, the GWP range of the PV systems is between 49.4 g CO_2 eq./kWh to 122.6 g CO_2 eq./kWh (Figure 14). Most of the emissions (>85%) are from the production process, more specifically, from the energy-intensive purification process of deriving electronic-grade silicon from metallurgical grade silicon. Greenhouse gas emissions from manufacturing the cathode and anode for lead-acid batteries are also relatively high, accounting for 23% and 33% of production emissions for the solar home system and mini-grid system, respectively. The incumbent case assumes low rates of recycling due to the absence of efficient end-of-life processes at baseline. At baseline, recycling of scrap aluminium, steel, and copper displaces greenhouse gas emissions in other industrial processes equivalent to 45% of the avoided virgin materials.

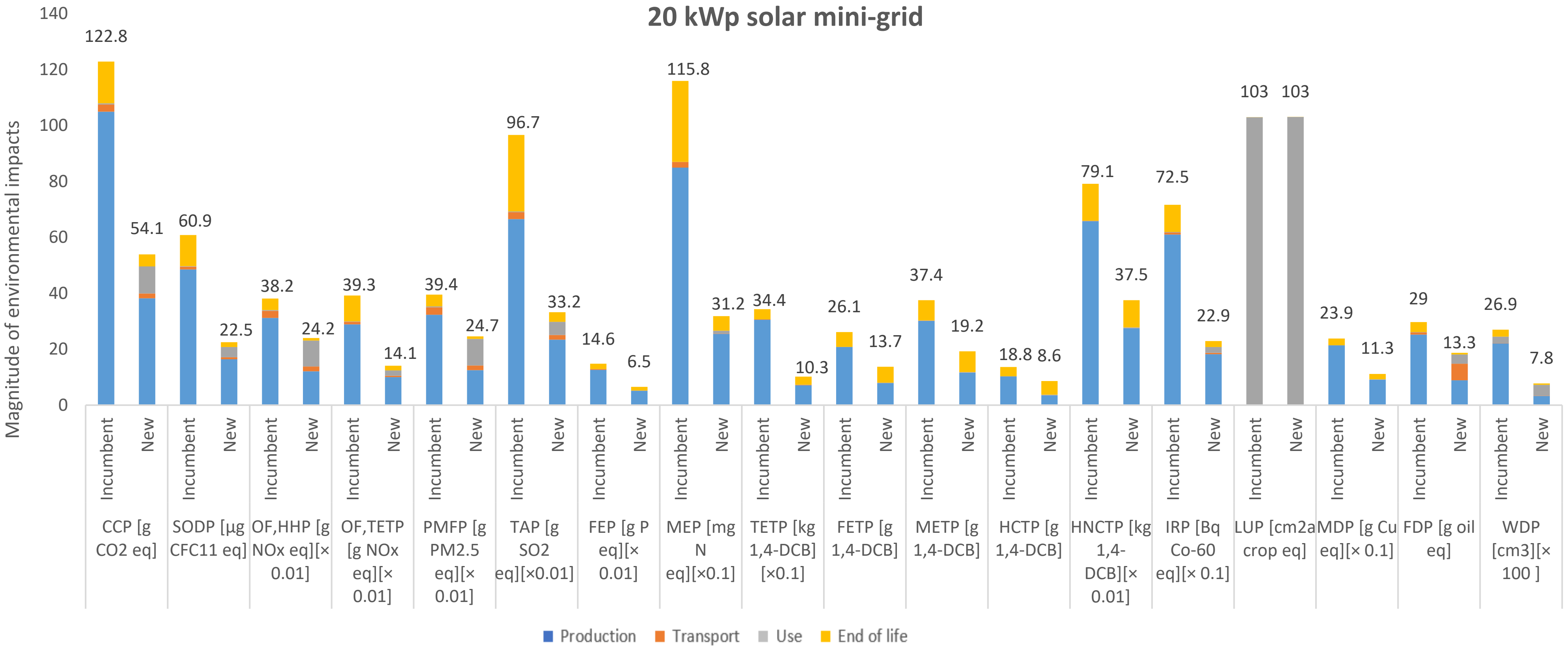
The business model innovation scenarios had significant improvement on the CCP although its impacts are still notable. Cumulative greenhouse gas emissions reduce significantly by 25% to 55% with a CCP range of 33.8 g CO_2 eq./kWh to 65.3 g CO_2 eq./kWh in the business model innovation scenarios (Figure 14). The product life extension propositions and closed-loop recycling scenarios displace significant production emissions upstream i.e., 24% solar home system, 42% industrial-scale PV, 44% commercial-scale PV, and 63% mini-grid. The total amount of greenhouse gas emitted upstream is determined by the fraction of primary materials produced to make up for recycling inefficiencies. A high recycling rate of lead-acid batteries lowers production emissions considerably for off-grid systems (e.g., the mini-grid), which require relatively large storage capacities.

4.3.2.2 Water and soil pollution (FEP, MEP, TAP)

Freshwater and marine eutrophication arise from chemical oxygen depletion following the release of PO_4^{3-} and NO_x in water, while terrestrial acidification is a result of air emission of SO_2, NO_x, NH_4, and H_2SO_4. In both incumbent and business model innovation scenarios, emissions from the energy-intensive production process that relies on fossil fuels are the main hotspot for acidification and eutrophication. Landfilling is responsible for the leaching of NH_4^+ and NO_3^- in water from polypropylene used in lead-acid batteries. The leachate is responsible for significant MEP in incumbent mini-grid and solar home system waste treatment scenarios, i.e., 25% and 52% of total MEP impacts. Emissions from high recycling rates and incineration in the business model innovation scenarios mostly increase the end-of-life eutrophication and acidification potential, particularly NH_4^+ emission from glass reprocessing. Overall, the business model innovation scenarios result in environmental benefits in the three impact categories (see Figure 14) and are credited for avoiding emissions upstream.

4.3.2.3 Air pollution (SODP, PMFP, POFP HH, POFP ET)

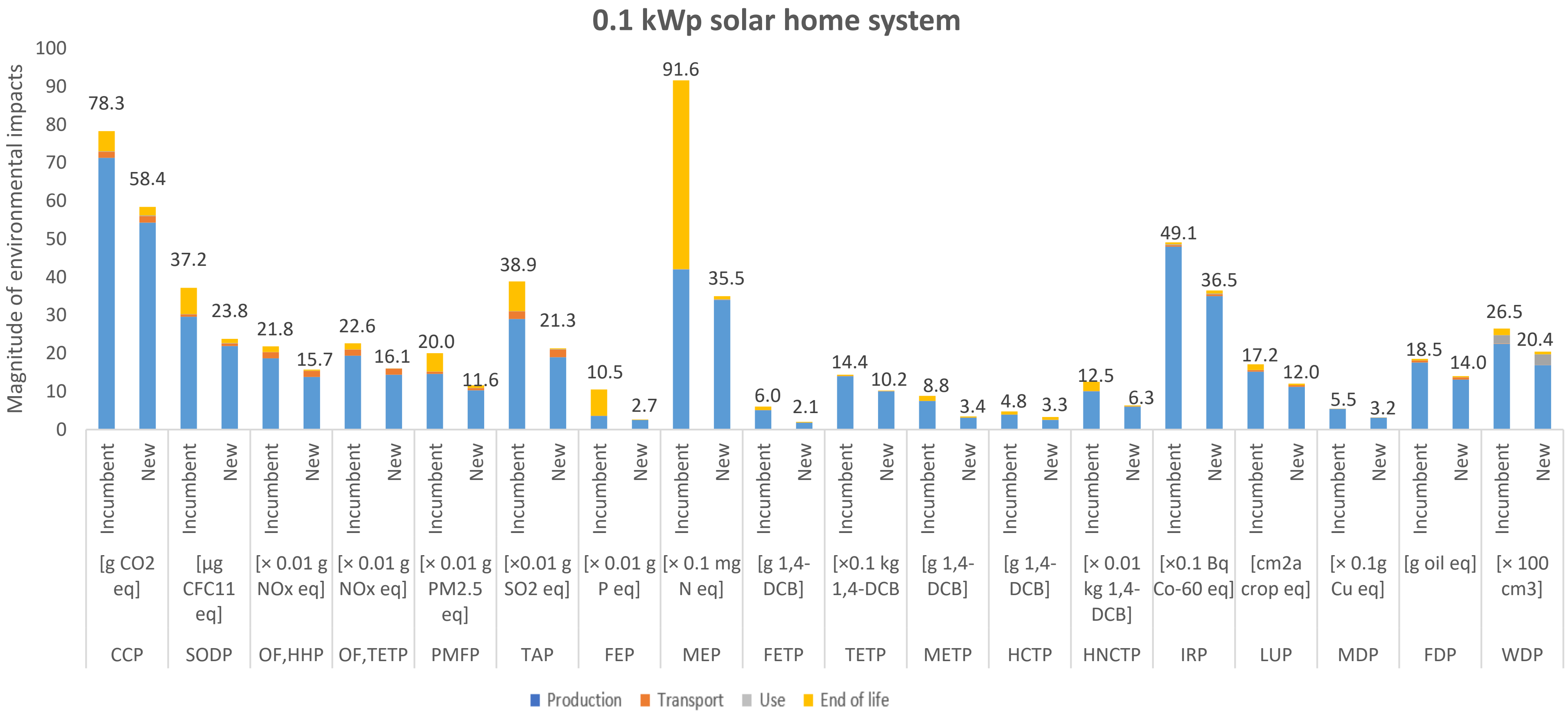
Air pollution impacts decrease in the business model innovation scenarios, compared to the incumbent business models, as shown in Figure 14 (please also see the caption in Figure 14 for impacts nomenclature used in this and other sections). The range of SODP of the solar PV systems at baseline is 23.4 to 60.9 µg CFC11 eq./kWh and decreases by 36% to 63% in the business model innovation scenarios. Ozone-depleting substances that cause SODP are from refrigerants such as $CHClF_2$ used in the production of polyurethane and polystyrene for encapsulating the solar cell. SODP at the end-of-life is mainly from the emission of bromine compounds during waste transportation, N_2O from the recycling of copper as well as the release of CFCs from disposed plastic foams. Incineration of polymers with electricity recovery results in benefits of between -2.2 and -3.6 µg CFC11 eq./kWh for SODP from avoided compounds such as HCFCs in the business model innovation scenarios except for the solar home system and mini-grid. In the mini-grid case, the benefits of incineration are counteracted by high N_2O from copper recycling.



(a)

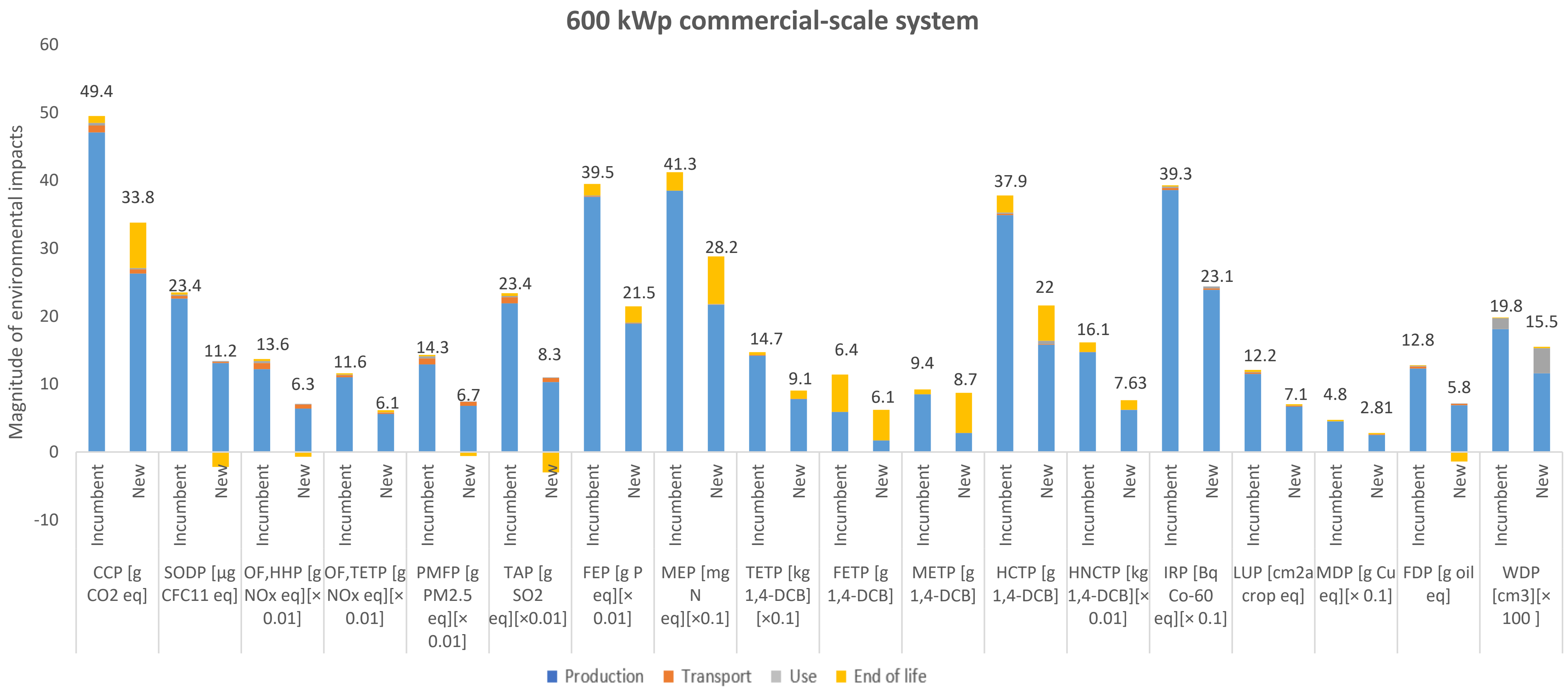
Figure 14: Life cycle environmental impacts of solar PV systems in the baseline (incumbent) and business model innovation (new) cases.

The impacts are expressed per kWh of electricity generated. Some impacts have been scaled to fit and actual values can be obtained by multiplying with the factors given in brackets. CCP: climate change potential; ODP: ozone depletion potential; IRP: ionizing radiation potential; POFP, HH: photochemical ozone formation potential, human health; POFP, TE: photochemical ozone formation potential, terrestrial ecosystem; TAP: terrestrial acidification potential; FEP: freshwater eutrophication potential; TETP: terrestrial ecotoxicity potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; HTCP: human toxicity carcinogenic potential; HTNCP: human non-carcinogenic toxicity potential; LUP: land use potential; MDP: mineral depletion potential; FDP: fossil depletion potential; WDP: water depletion potential.



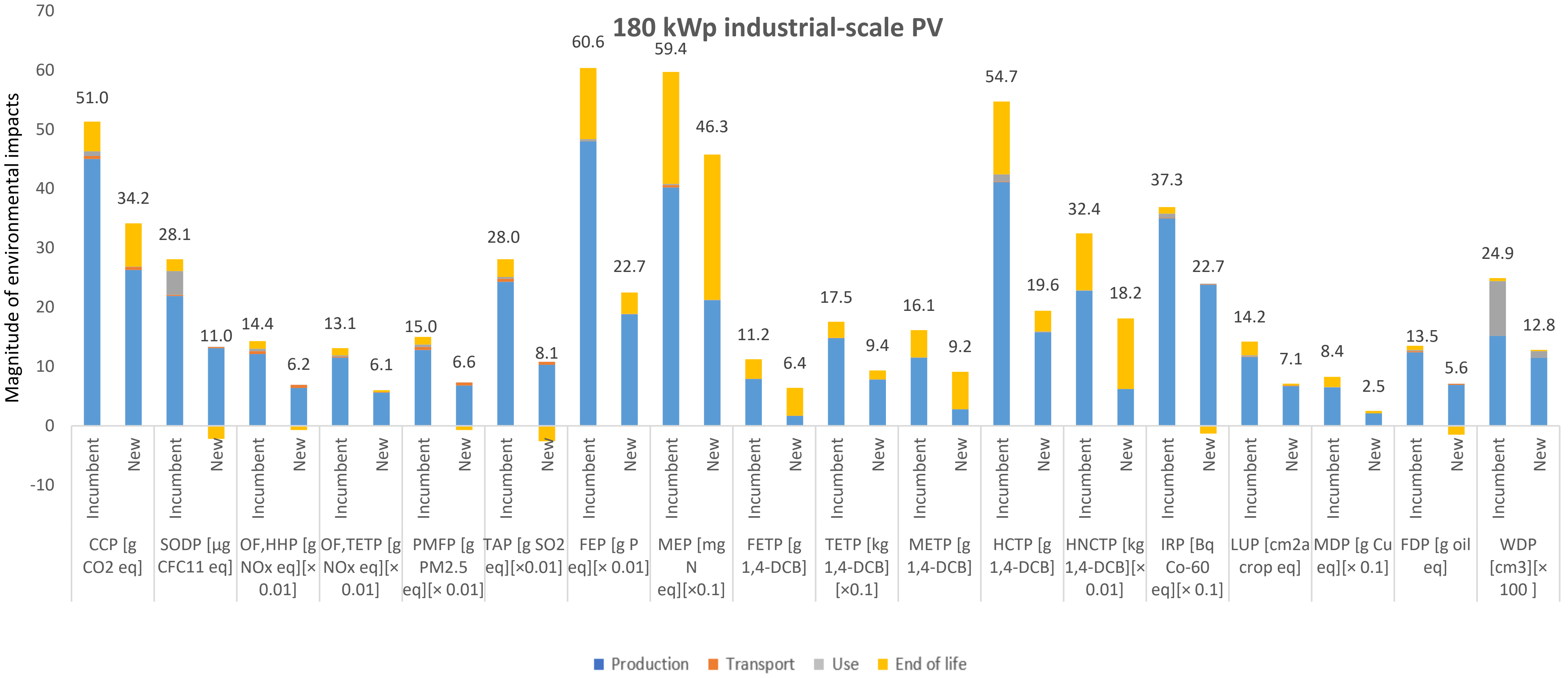
(b)

The impacts are expressed per kWh of electricity generated. Some impacts have been scaled to fit and actual values can be obtained by multiplying with the factors given in brackets. CCP: climate change potential; ODP: ozone depletion potential; IRP: ionizing radiation potential; POFP, HH: photochemical ozone formation potential, human health; POFP, TE: photochemical ozone formation potential, terrestrial ecosystem; TAP: terrestrial acidification potential; FEP: freshwater eutrophication potential; TETP: terrestrial ecotoxicity potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; HTCP: human toxicity carcinogenic potential; HTNCP: human non-carcinogenic toxicity potential; LUP: land use potential; MDP: mineral depletion potential; FDP: fossil depletion potential; WDP: water depletion potential.



(c)

The impacts are expressed per kWh of electricity generated. Some impacts have been scaled to fit and actual values can be obtained by multiplying with the factors given in brackets. CCP: climate change potential; ODP: ozone depletion potential; IRP: ionizing radiation potential; POFP, HH: photochemical ozone formation potential, human health; POFP, TE: photochemical ozone formation potential, terrestrial ecosystem; TAP: terrestrial acidification potential; FEP: freshwater eutrophication potential; TETP: terrestrial ecotoxicity potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; HTCP: human toxicity carcinogenic potential; HTNCP: human non-carcinogenic toxicity potential; LUP: land use potential; MDP: mineral depletion potential; FDP: fossil depletion potential; WDP: water depletion potential.



(d)

The impacts are expressed per kWh of electricity generated. Some impacts have been scaled to fit and actual values can be obtained by multiplying with the factors given in brackets. CCP: climate change potential; ODP: ozone depletion potential; IRP: ionizing radiation potential; POFP, HH: photochemical ozone formation potential, human health; POFP, TE: photochemical ozone formation potential, terrestrial ecosystem; TAP: terrestrial acidification potential; FEP: freshwater eutrophication potential; TETP: terrestrial ecotoxicity potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; HTCP: human toxicity carcinogenic potential; HTNCP: human non-carcinogenic toxicity potential; LUP: land use potential; MDP: mineral depletion potential; FDP: fossil depletion potential; WDP: water depletion potential.

Emission of non-methane volatile organic compounds and NO_x in industrial processes, particularly the production of solar panels and lead-acid batteries, are the main hotspots for POFPHH and POFPTE, followed by recycling emissions. Landfilling and disposal in open dumpsites have a negligible contribution to POFPHH and POFPTE, therefore, in the absence of recycling, transport performs second-worst to production in these categories. The negative values in Figure 8 show that electricity recovery from incineration avoids POFPHH by not more than -7 mg NO_x eq./kWh. The overall aggregated benefits of these categories due to business model innovation are the percentage reduction from the baseline case.

PMFP during the production stage is mostly a result of emissions of NO, NH_3, SO_3, volatile organic compounds, nitrates, sulfates, and organic carbonaceous associated with the production of electricity from fossil fuels. The production stage accounts for at least 73% of PMFP with most emissions linked to manufacturing solar panels followed by lead-acid batteries. Bulk PMFP from the end-of-life occurs mainly from air emission of NO, SO_3, NH_3 from the recycling of lead and copper. PMFP impacts are reduced by up to 64% in the business model innovation scenarios due to the production of secondary materials in manufacturing.

4.3.2.4 Ecotoxicity (TETP, METP, FETP)

Ecotoxicity-related impacts are primarily from the emission of a broad range of toxic pollutants mainly from fossil fuel use during the production process, tributyltin compounds and rubidium during transportation, and leaching of lead and calcium from landfilled batteries at the end-of-life. The production stage is the main hotspot across the three ecotoxicity categories in all business models accounting for at least 46% in the baseline case. Particularly copper mining contributes to ecotoxicity impact categories due to the disposal of sulfudic tailings. The emission of toxic compounds from industrial recycling and refining (e.g., of glass, fossil fuel, and fly ash incineration of polymers) increases the end-of-life impacts of FETP and METP in the business model innovation scenarios.

4.3.2.5 Resource depletion (MDP, FDP, WDP)

MDP is reduced by 41% to 70% in the business model innovation scenarios as shown in Figure 14. MDP changes considerably between baseline and the innovation scenarios because of the assumed higher recycling rates in the latter. Shifting from product sales to leasing in the rent-to-own business models also reduces MDP because of high take-back rates. The production stage is the main hotspot in both cases, although its relative contribution to MDP is reduced in the business model innovation scenarios. For example, in the commercial-scale PV system, MDP of production is reduced from 0.5 g Cu eq./kWh (94% of total impacts) at baseline to 0.2 g Cu eq./kWh (83% of total impacts) in the business model innovation scenarios because of the higher recycling and material recovery rates.

Most FDP in incumbent business models (>86%) occurs from heat, electricity, and oil use during the production stage. Particularly due to the energy-intensive process of manufacturing solar cells and polymers for multicrystalline solar panels. Significant fuel consumption in transoceanic ships and road trucks places transport as the next hotspot of FDP, although the overall contribution of transport to this category is lower than 12%.

FDP reduces with higher recycling rates and electricity recovery from the incineration process in the business model innovation scenarios because of a reduction in hydrocarbon fuel extraction and use. WDP varies depending on the volume used to wash solar panels. WDP is highest during production at baseline but shifts considerably to the use stage in the business model innovation scenarios due to the extension of the lifetime of PV systems. For example, tap water requirements for washing a 180 kWp PV installation increase from 916 cm^3 /kWh to 1855 cm^3 /kWh. WDP also varies depending on the size and lifetime of the PV installation. In the solar home system, the use stage accounts for 14% of WDP in the business model innovation scenarios because of the relatively small surface area. In larger systems, like mini-grid and industrial-scale systems, the use stage accounts for 50% and 61% of the WDP, respectively.

4.3.2.6 Land use (LUP)

LUP of the PV systems in each business model is conditional on the type of installation during the use stage. Ground-mounted systems like the solar mini-grid have high LUP during the use stage in both scenarios (i.e., 103 m^2 a crop eq./kWh accounting for 99% of the LUP impact). The use stage LUP of roof-mounted installations such as the commercial and industrial-scale PV systems is less than 1% because the burden is borne by existing buildings that fall outside the system boundary. Land conversion and occupation for landfills and open dumpsite purposes account for a small proportion of LUP (<16%) during disposal across all incumbent business models. Disposal is constrained by the availability of land and special facilities for containing hazardous waste e.g., sludge from recycling processes, which in turn has a direct bearing on other impact categories. Diverting waste from landfills in the business model innovation scenarios mainly reduces land requirements by 30% to 50%.

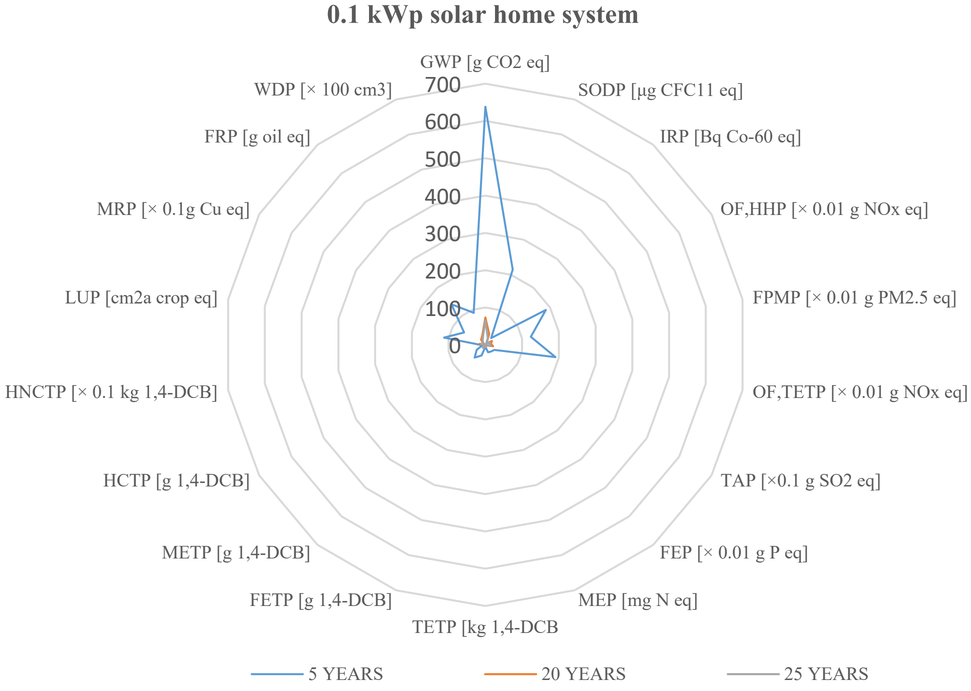
4.3.2.7 Human health (IRP, HCTP, HNCTP)

The IRP of the four PV systems under the business model innovation scenarios decreases by between 26% to 68% (Figure 8); most reduction is attributed to displacing nuclear energy upstream. The use of nuclear energy to produce electricity for manufacturing solar panels emits large quantities of radionuclides such as Radon-222. Electricity recovery from incineration displaces the emission of radionuclides (e.g., iodine-131, strontium-90), hence, is beneficial to IRP. HCTP and HNCTP stem from exposure to carcinogens and non-carcinogens, mainly from copper processing. The production of copper and its alloys for use in components of electric installation, solar panels, and inverters emit carcinogens like cadmium and chromium into water bodies and are the main hotspot for HCTP at baseline. As shown in Figure 14, HCTP decreased by between 32% and 64% with business model innovations, mainly attributed to a reduction in the emission of high volumes of toxic substances such as mercury C_6Cl_6 from steel processing. Business model innovation decreases HNCTP in the industrial-scale and mini-grid systems by 43% and 53%%, respectively, due to the avoided production of copper.

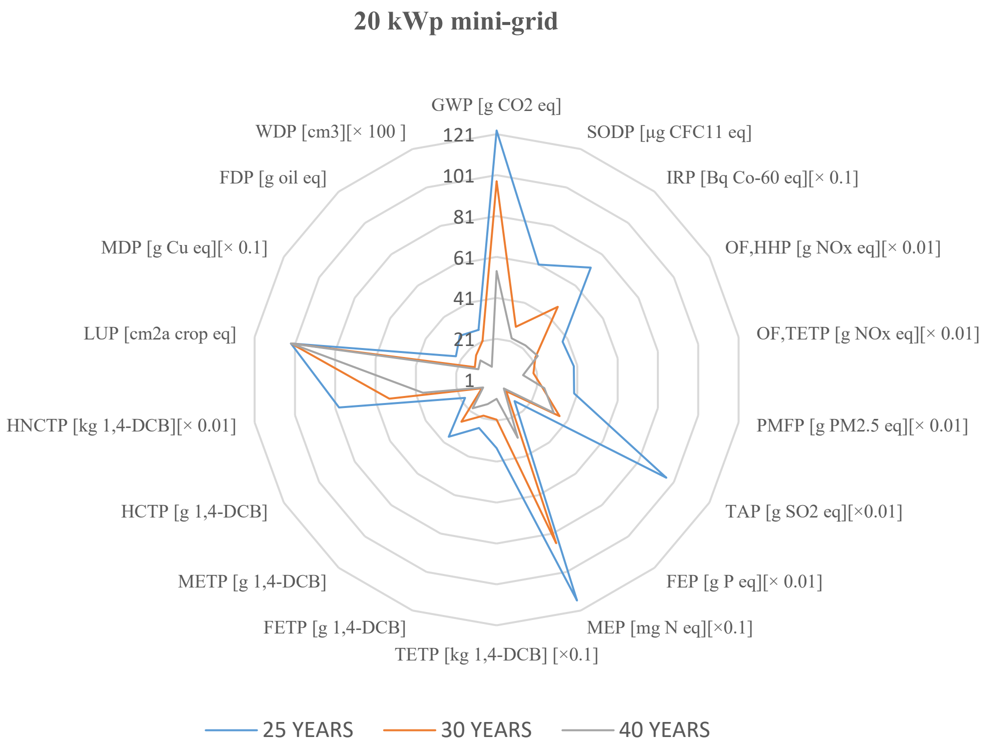
4.3.3 Sensitivity analysis

The variation of environmental impacts of no-recycling for rent-to-own, partial recycling for the other business models, and high recycling rates in the business model innovation scenarios have been evaluated in the preceding sections. Although the use stage is the least impactful compared to production and recycling, a sensitivity analysis shows that the lifetime of solar PV systems has a significant effect on the magnitude of environmental impacts as shown in Figure 15a-d. The figure shows how the magnitude of each impact category in each PV system changes when the lifespan is varied. It should be highlighted that the lifetime of the solar home system in the rent-to-own business model is assumed to be 20 years going by manufacturer's and company specifications although shorter lifespans (of less than five years) are common in the absence of maintenance (Cross and Murray, 2018). For example, previous studies (e.g., ibid) found that without maintenance services, small customer-owned solar systems in Kenya tend to be faulty a few years after purchase. Assuming a lifetime of 5 years for the solar home system, environmental impacts increase by more than 100% in all impact categories relative to the baseline case (Figure 15). For example, metal depletion potential increases to 6.5 g Cu eq./kWh (92% increase) while climate change potential increases to 638 g CO_2 eq./kWh (a more than 100% increase). The increase can be attributed to low energy production hence an increase in impacts per kWh (Peng et al., 2013) i.e., the systems are not in operation long enough to displace the energy and carbon associated with their lifecycle.

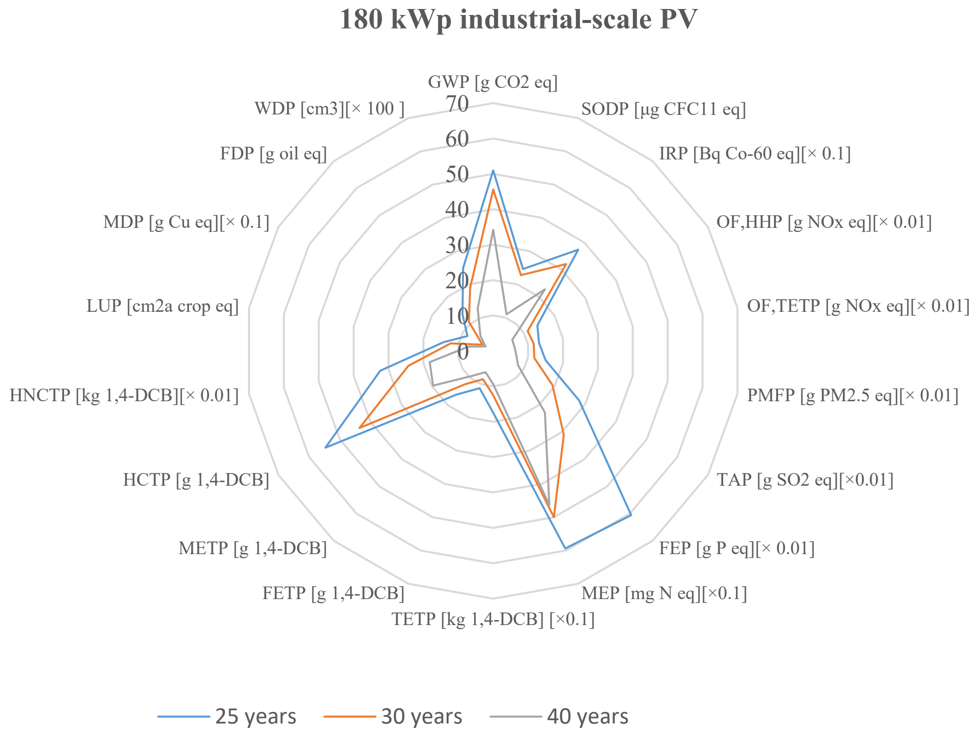
The typical lifetime of solar PV in the market is 30 years (IRENA and IEA PVPS, 2016). Assuming a 30-year lifetime, Figure 15 shows how the impact categories compare between the baseline and business model innovation cases. In general, there is an inverse relationship between the lifetime of solar PV systems and the magnitude of environmental impacts in most categories. In the mini-grid, these impacts decrease by 10% to 66% due to the presence of batteries that already have a high recycled content of lead and copper at baseline; hence, resulting in a low cumulative burden. The embodied impact of recycling factored with the energy yield of the PV systems during its use over 30 and 40-year time frames bring about a decrease in impact categories (Figure 15).



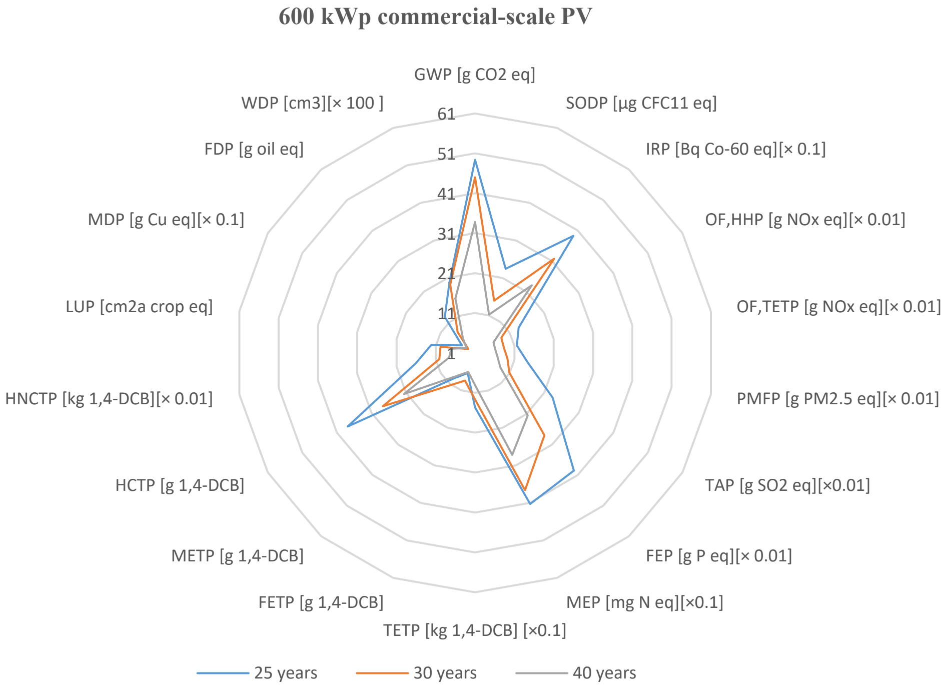
(a)


20 kWp mini-grid
GWP [g CO2 eq]
SODP [µg CFC11 eq]
IRP [Bq Co-60 eq][× 0.1]
OF,HHP [g NOx eq][× 0.01]
OF,TETP [g NOx eq][× 0.01]
PMFP [g PM2.5 eq][× 0.01]
TAP [g SO2 eq][×0.01]
FEP [g P eq][× 0.01]
MEP [mg N eq][×0.1]
TETP [kg 1,4-DCB] [×0.1]
FETP [g 1,4-DCB]
METP [g 1,4-DCB]
HCTP [g 1,4-DCB]
HNCTP [kg 1,4-DCB][× 0.01]
LUP [cm2a crop eq]
MDP [g Cu eq][× 0.1]
FDP [g oil eq]
WDP [cm3][× 100]
121
101
81
61
41
21
1
25 YEARS
30 YEARS
40 YEARS

(b)


180 kWp industrial-scale PV
GWP [g CO2 eq]
SODP [µg CFC11 eq]
IRP [Bq Co-60 eq][× 0.1]
OF,HHP [g NOx eq][× 0.01]
OF,TETP [g NOx eq][× 0.01]
PMFP [g PM2.5 eq][× 0.01]
TAP [g SO2 eq][×0.01]
FEP [g P eq][× 0.01]
MEP [mg N eq][×0.1]
TETP [kg 1,4-DCB] [×0.1]
FETP [g 1,4-DCB]
METP [g 1,4-DCB]
HCTP [g 1,4-DCB]
HNCTP [kg 1,4-DCB][× 0.01]
LUP [cm2a crop eq]
MDP [g Cu eq][× 0.1]
FDP [g oil eq]
WDP [cm3][× 100]
70
60
50
40
30
20
10
0
25 years
30 years
40 years

(c)



(d)

Figure 15: A comparison of how the life cycle environmental impacts of solar PV systems are affected by different lifetimes. The impacts are expressed per kWh of electricity generated. See Figure 8 for impacts nomenclature.

4.3.4 Comparison with other studies

Comparison of the findings of this study with other studies is difficult because using LCA in the analysis of solar energy business models is still a nascent area of research. Even when LCAs focus only on the solar PV systems, factors such as variations in product systems specifications, geographical contexts, assumptions, number of impact categories, or system boundaries also make comparisons of PV systems challenging. Figure 16 shows the environmental performance of solar PV systems in Africa obtained from a systematic review by Mukoro et al. (2021). Although the functional units are similar to this study, the results show considerable variation in the impact categories mainly due to different system sizes, technology composition (e.g., hybrid systems), and life cycle stages. The higher CCP values are for pairing PV with diesel generation in a mini-grid in Kenya (Bilich et al., 2017) and for short-lived organic solar PV (Espinosa et al., 2011). The findings of this study are within the ranges in literature (Figure 16).

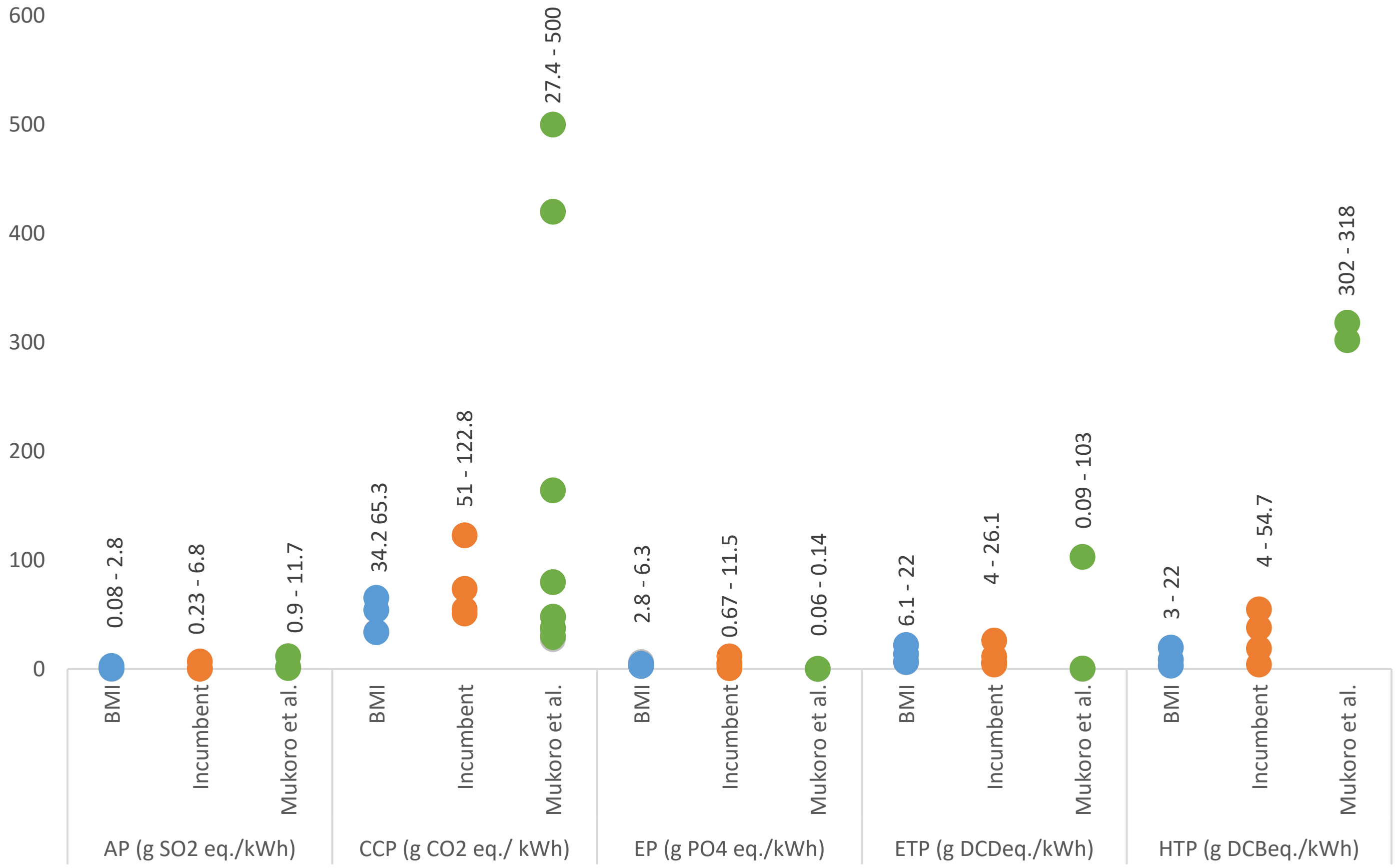


Figure 16: Environmental impacts of solar PV systems in Africa adapted from Mukoro et al. (2021) compared to this study. See. Figure 8 for impacts nomenclature. BMI- business model innovation.

The results of this study support literature findings (e.g., Sica et al., 2018) that make a case for the environmental sustainability of CE in solar PV applications. The production stage is the main hotspot for environmental impacts as found in previous studies, mainly impacts of the solar panel (e.g., Aberilla et al., 2020; Gaete-Morales et al., 2018; Ito et al., 2016). These impacts can be minimised by redesigning value propositions and supply-and-demand-side aspects to extend product lifetimes and increase recycling. The analysis of the incumbent and CE business model should not be limited to the selected business models or solar energy companies in Kenya. The share of decentralised solar PV capacity in Africa has been increasing annually from 1.09 MW in 2011 to 1.05 GW in 2020 (IRENA, 2021) primarily due to business models such as prosumer, rent-to-own, pay-per-service unit, etc. (Mukoro et al., 2022). This increase provides an incentive to extend the analysis to decentralised and on-grid business models across the continent to assess their suitability for substituting incumbents. This study is limited to the four business models investigated, therefore, the environmental potential of other archetypes not presented in the sample is unknown.

4.4 Conclusions

This study presents for the first time a new framework for performing environmental assessments of business models (EBuM). The EBuM framework integrates the life cycle assessment (LCA) methodology to quantify environmental impacts, the business model canvas to provide a structured assessment of business models and business model innovation, and participatory decision-making to include multiple stakeholders' perspectives. While LCAs and business models are separately extensively researched, studies that combine them to quantify the environmental impacts of business models to inform decision-making are few. This novel framework addresses the under-researched area by providing sequential steps for assessing the environmental impacts of business models.

The EBuM framework is tested on solar energy companies in Kenya to assess, for the first time, the environmental performance of incumbent solar energy business models in Kenya (i.e., rent-to-own, pay-per-service-unit, prosumer, and EPC with leasing-to-own) relative to their CE substitutes. The business models are for a solar home system, a mini-grid, commercial-scale, and industrial-scale photovoltaic (PV) systems. Findings show that the environmental impacts of incumbent solar energy business models are generally higher than their CE substitutes for three reasons. First, the incumbent business models only focus on the use of solar PV systems and exclude other life cycle stages. Second, shorter lifetimes of the solar PV systems at baseline than their CE substitutes increase environmental impacts. Third, low recycling efficiencies and rates at baseline result in high demand for primary materials in energy-intensive production processes, resulting in significant impacts, particularly for resource depletion and climate change.

Findings show that integrating environmental sustainability into the value proposition (e.g., shifting from product sales to renting with take-back) gives better environmental outcomes across all impact categories. Transforming incumbent business models to be CE-oriented leads to significant reductions in environmental impacts. For example, climate change impacts are reduced by about 25% to 55%, while metal depletion by 41% to 70%. However, these benefits are dependent on two key aspects that were not evaluated in this study i.e., customer acceptance of circular business models and the financial viability of companies adopting them.

This study supports environmental assessments in companies through the lens of business model innovation. The limitation of the EBuM framework is that it calls for an interactive multistakeholder and interdisciplinary approach throughout the problem-solving and decision-making process, thus, can be deemed complex. Besides, it brings together two very different research areas (i.e., life cycle assessment and business model analysis) which are not commonly paired. Conducting environmental assessments of business models using standardised methods such as life cycle analysis is not always straightforward. For example, LCA guidelines are best applied to product systems and the challenge of using them on business models is the definition of the reference system, functional unit, and system boundaries (Kjaer et al., 2016). Furthermore, the unavailability of data, complex value chains, assumptions, and the use of average datasets from generic databases adds to the complexity of performing LCAs of business models (Lindahl et al., 2014; Manninen et al., 2018). This limitation can be overcome by using guidelines such as those developed by Kjaer et al. (2018) or streamlining the analysis. Another limitation of the study is that the EBuM framework is tested on a small number of business models adopted by developers and distributors in Kenya. The scope of this study excluded the application of the framework in cost-efficiency assessments and customer engagement which are key determinants of the practicality of adopting circular business models. Thus, the potential environmental benefits of these business models can be affected by social and financial reasons.

The EBuM framework is designed to take into account stakeholders' concerns and priorities when evaluating environmental impacts and mitigation pathways. Future studies are needed to test and validate the framework beyond environmental assessments by evaluating the social and economic sustainability of circular business models. For example, multicriteria decision analysis can be used to determine trade-offs across environmental, social, and economic aspects of business model innovation to come up with feasible business substitutes.

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Chapter 5: Discussion

In this section, the answers to the key research questions are discussed based on the three presented papers:

- Paper 1 in Chapter 2: Life cycle assessment of renewable energy in Africa.
- Paper 2 in Chapter 3: A review of business models for access to affordable and clean energy in Africa: do they deliver social, economic, and environmental value?
- Paper 3 in Chapter 4: Environmental assessment of business models: the EBuM framework and its application to solar energy in Kenya.

A critical reflection of the research question is given alongside the key findings of each paper in this chapter. Section 5.1 evaluates the key research questions of this research and how they are addressed in the respective papers. Section 5.2 discusses the implications of this research to policy, business, and the industry while section gives the contributions of this study to the body of knowledge, including the dissemination approach so far.

5.1 Research questions

Evaluating the environmental impacts of renewable energy business models in Africa is critical to mitigating the unintended negative environmental impacts of the clean energy transition and potentially resulting in positive social and economic benefits. This research performed systematic literature reviews (Paper 1 and Paper 2), developed a new framework, and applied it to the solar energy sector in Kenya (Paper 3) to achieve its aim of investigating the potential environmental impacts of renewable energy business models. The answers to the key research questions and key findings are discussed below.

RQ1: What are the environmental impacts of, and the status of LCA research on renewable energy in Africa?

Findings of LCA of renewable energy (Paper 1) show that even for the same technology type, the magnitude of environmental impacts varies considerably due to variations in geographical characteristics, study contexts (e.g., specifications of product systems), system boundaries, completeness in impact coverage, and energy yield (Mukoro et al., 2021). LCA research in the reviewed documents mainly covered first-generation bioenergy and solar photovoltaic systems in Africa while the other renewable energy sources remain largely unresearched. The narrow research focus does not give the full potential of environmental impacts of the sector, particularly for regional and local impacts that occur closer to the source of extraction or emission. A narrow focus is also observed in impact coverage where climate change is the primary focus of most studies mainly due to the global political targets on mitigation (UNFCCC, 2015). For example, the CCP range for liquid biofuels is between 3.4 g CO_2 eq./kWh to 1560 g CO_2 eq./kWh (Figure 3). The wide range is due to a combination of the aforementioned factors. The CCP range for solar PV is 27.4 g CO_2 eq./kWh to 1100 g CO_2 eq./kWh (Figure 3). The use of diesel generators in hybrid solar PV mini-grids is responsible for the high CCP. There were only two studies on wind energy in Paper 1 (Al-Behadil et al., 2015; Andrae et al., 2012), one of which was non-hybrid with a CCP of 4.7 g CO_2 eq./kWh. Hence, generalisation cannot be made.

Other impact categories that are restricted to the regional and local scale (e.g., pollution of ecosystems and land use, respectively) are underrepresented in existing studies. These impacts which comprise eutrophication, acidification, resource depletion, human health, toxicity, particulate matter formation, and land use, are relevant and significant to the continent because they vary widely depending on the sensitivity of the regional or local ecosystems. In general, most commercially available life cycle inventory databases have spatial datasets that are well designed for a few countries or specific regions (mostly North American and European), thus, their applicability in Africa may be limited and associated with uncertainties because of data gaps.

The reviewed studies show that the production stage is the main hotspot of environmental impacts (i.e., more than 50% in most impact categories) followed by the end-of-life in non-bioenergy renewable energy systems. When observed through the lens of business models in the empirical study, most impacts occur on the supply side from the energy and resource-intensive process and related emissions. The demand side is also an environmental hotspot although the magnitude of its impacts is contingent on the value proposition and the key activities on the supply side of business models. Unlike non-bioenergy renewable energy systems, the production and use stages are identified as hotspots in bioenergy systems in Paper 1. For example, some studies found the crop cultivation stage to be the main hotspot when land use impacts were taken into consideration. In studies that did not factor in land use and negated sequestrated carbon, biodiesel combustion in engines made the use-stage the most damaging. In such cases, harmonisation of LCAs can help address these inconsistencies and identify trade-offs in the inclusion or exclusion of land-use impacts.

Paper 1 section 2.3.2.4.2 recognises that different types of functional units for the same renewable energy technology and system boundary definitions cause variation in the results, thus, affecting the recommendations. If incorrectly selected, functional units can lead to inaccurate results and recommendations (Sills et al., 2020). Paper 3 shows that while the relationship between the lifespan of solar PV systems and environmental impacts is mainly inverse (section 4.3.3), business model types (e.g., traditional versus circular) significantly affect the magnitude of impacts. Such factors should also carefully be considered alongside functional units in the interpretation of results and recommendations because they affect the effectiveness of mitigation decisions.

From Paper 1, it became apparent that the applicability and reliability of LCAs of renewable energy in Africa are affected by methodological issues such as inadequately defined goals and functional units, and non-transparent system boundaries and inventories. Likewise, choices such as incomplete coverage of impact categories due to prioritisation may result in burden-shifting. Paper 3 avoids this issue by calculating all impact categories. Few processes that are specific to African countries are already included in the Ecoinvent database e.g., datasets for low and medium voltage electricity. However, the coverage of processes is still low and most LCAs largely rely on global averages. The lack of life cycle inventory datasets for Africa raises concerns about the geographical representativeness LCAs. Paper 3 primarily used global datasets from Ecoinvent and adapted them to the study context.

Recommendations for mitigating environmental impacts of renewable energy mostly focus on reducing the burden of production and the end-of-life which are the main hotspots. Paper 3 finds that these two hotspots present the greatest potential for mitigating environmental impacts by switching from linear to CE systems. While Paper 3 shows the potential of CE at the micro-level (i.e., firms), Aguilar et al. (2021) give a macro-level perspective of transitioning to a CE, thus, supporting the theory that CE can potentially have positive environmental consequences. However, it should be noted that the LCA outcomes of CE may vary case by case depending on context. The EBuM framework can be useful in this regard because it can be applied to different sectors.

The conclusion is that the systematic literature review of LCA of renewable energy in Africa provides a comprehensive assessment of the status quo and recommendations that can be used in decision-making contexts. However, individual LCA results should be applied with caution given the concerns discussed. A sensitivity or uncertainty analysis may be necessary to handle trade-offs associated with methodological choices, hotspots, coverage of impact categories or life cycle stages, and product systems. Besides, the accuracy of LCAs will depend on addressing methodological challenges and improving the geographical representativeness of data.

RQ 2: What types of business models for renewable energy are adopted in Africa and to what extent do they create social, economic, and environmental value?

In general, renewable energy business models demonstrate the business case for providing energy products and services as well as innovations that incentivise the integration of renewable sources in existing power systems (IRENA, 2020). These business models serve on-grid and off-grid markets to increase the uptake of renewable energy, boost consumer choices and include consumers in energy production and retail (ibid). From the reviewed studies, business models adopted on the continent are for energy access (e.g., rent-to-own, renting, leasing, pay-per-service-unit, swarm electrification, electrification seeds), grid decarbonisation (e.g., prosumer, store-on-grid, engineering procurement and construction), and bioenergy feedstock production (e.g., contract farming, outgrower schemes, plantation farming, hybrid model). The business models in the reviewed studies are by no means exhaustive because of newer entrants such as peer-to-peer trading, aggregators, and community energy.

Incumbent business models for renewable energy are primarily designed to deliver social and economic value. This study identified that environmental value is only evidenced to a lesser extent, mainly in the use-stage of renewable energy technologies e.g., by displacing diesel generators. The environmental impacts of production, transport, and disposal are not documented, except for land-use impacts of bioenergy crop cultivation. Despite environmental impacts being underrepresented in current literature as discussed in Paper 2 (Chapter 3), they are significant and can considerably be mitigated at the company level (as shown in Paper 3, Chapter 4). Empirical findings broaden the understanding of drivers and barriers to the viability of different types of business models in Africa and to what extent they deliver on sustainability.

PSS business models are innately designed to have better environmental performance than traditional models by capitalising on the benefits of servitisation (Barquet et al., 2016; Mont, 2002). However, PSS can have both positive and negative environmental consequences and must be combined with LCAs to quantify their impacts. For example, evidence Paper 2 shows that some models of PSS (e.g., renting or leasing) can be counter-productive to their intended benefit of resource efficiency when customers improperly use products rendering them obsolete prematurely. However, other than this research, there is sufficient evidence (e.g., Tukker, 2015) that the leasing model can be resource-efficient. The outcome, positive or negative, depends on the lifetime of products, waste management, and the amount of virgin materials not used in production. The findings answering this research question provide considerations for designing renewable energy business models that deliver on environmental sustainability. For example, environmental benefits can be realised by combining sharing platforms for leasing, renting, product optimisation, and circular supply chains.

RQ3: How can LCA be applied in the analysis of business models?

This study created an iterative framework that integrates LCA, participatory decision-making, and business model innovation to measure the environmental impacts of business models. The EBuM framework makes it possible to create solutions to research problems that cannot be effectively covered by one discipline. For example, the LCA methodology is designed for the analysis of product systems while business models look at interconnected systems of creating and delivering products and services to customers for financial gain. Combining these two fields alongside stakeholders' participation gives a tool that can be adapted to different study contexts.

Unlike product systems, defining the reference systems, functional units, and system boundaries is a challenge in pairing LCA with business models (Kjaer et al., 2016). The EBuM framework is applied to solar energy companies in Kenya to qualitatively and quantitatively analyse the environmental impacts of business models. The framework allows company staff to be involved in the creation of solutions and making decisions that are aligned with the companies' vision and are potentially economically feasible. For example, factors such as complex service and reverse logistics due to the wide geographical distribution of solar home systems in remote areas disincentivise recycling in rent-to-own business models (Paper 3, section 4.2.2.3.2). Financial and social assessments that determine the feasibility of take-back schemes are necessary in this case. This research shows that comparing the baseline case and the business model innovation scenarios provides the basis for mitigating environmental impacts at the company level. However, the changes should be evaluated alongside social and economic factors to create a business case. Quantitative assessments of business models are essential for hotspot identification and to evaluate the effectiveness of decision-making. For example, quantifying the environmental impacts of incumbent business models informed mitigation decisions that resulted in the proposed CE alternatives (Paper 3).

Apart from EBuM, other approaches have been created by, for example, Böckin et al. (2022), Goffetti et al. (2022), Kjaer et al. (2018), and Mendoza et al. (2017) to investigate business models from an environmental viewpoint. These approaches vary considerably and may be suitable only for a specific type of analysis. For example, the methodology by Böckin et al. (2022) is suitable for environmental impacts from an economic standpoint i.e., profit, while the guidelines by Kjaer et al. (2018) describe the specific considerations of performing LCA of PSS business models. Mendoza et al. (2017) created a framework that integrates backcasting and eco-design to evaluate circular business models. Combining LCA and business models is still a nascent area of research and no one framework may fully satisfy all requirements of conducting analyses in different contexts. In this case, a variety of approaches may be necessary to give options that are suitable for varied contexts. Existing frameworks can also be simplified, adapted, combined, or used in part to suit study contexts as opposed to creating new methodologies.

RQ4. How can business model innovation and circular economy be leveraged to mitigate the environmental impacts of traditional business models?

Business model innovation can mitigate the environmental impacts of all PV systems in all impact categories in this study (Figure 14). In this research, business model innovation is assessed through the lens of CE. Two steps are required to this end. First, quantifying the environmental impacts of traditional business models (i.e., the baseline case). Second, stakeholder engagement to evaluate the baseline case, propose circular business models, and quantify their environmental impacts (i.e., the business model innovation scenarios).

(i) Baseline case

This research shows that in order to identify the sources of environmental impacts in incumbent business models, the value proposition, the supply-side (i.e., key activities, key resources, and key partnerships, and the demand-side (customer segments, customer relationships, and channels) must be assessed. This assessment is important because these blocks of business models create and deliver renewable energy products and services to customers and have the greatest potential to reduce resultant impacts. The contribution of the demand-side aspects to overall environmental impacts directly depends on the supply-side and value proposition. In the baseline case, the business models were significant sources of environmental impacts mainly due to their linear economy orientation or the integration of CE principles to a lesser extent. These findings prompted the assessment potential of business model innovation in achieving better environmental outcomes for companies throughout the lifecycle of their products.

(ii) Business model innovation scenario

Academic literature has extensively built a case for CE in relation to resource efficiency, obsolescence, and waste reduction. This study has gone a step further to quantify the environmental potential of integrating the principles of CE in business models, taking to account companies' priorities and outlook. In this study, business model innovation is achieved by slowing (i.e., adopting service-based value propositions like energy-as-a-service), closing (i.e., implementing take-back schemes to facilitate recycling solar PV systems), and narrowing (i.e., collaboration with the supply chain to ensure secondary materials are used in the production process) loops through stakeholder collaboration and coordination along the value chain. The business model innovation scenarios show that indeed CE interventions can reduce the environmental impacts of incumbent business models in the case companies (Figure 14).

The benefits of business model innovation can be achieved under three sets of conditions. The first condition is to apply the principles of CE. For example, (i) resource efficiency through intensified use of products (e.g., maintenance for longevity to reduce the demand for new products), (ii) implementing PSS with take-back schemes to displace resource-intensive traditional models, and (iii) closed-loop recycling to reduce the demand for virgin materials. The second condition is to perform LCA to ensure that the environmental impacts of transitioning to circular business models are lower than the baseline case.

Whilst this study highlights the circumstances under which CE is beneficial in the given study context, Loon et al. (2021) draw attention to instances when adopting CE interventions may be more damaging. For example, product life extension is most beneficial if the production stage is the main hotspot of environmental impacts and least beneficial if the use stage accounts for the highest burden. Besides, extending the useful life of products may become a hotspot if they degrade over time resulting in high consumption of resources and energy or if new energy-efficient products are introduced in the market. In these examples, it is beneficial to replace the products rather than prolong their life.

The third condition, which was beyond the scope of this study, is that social and economic factors must be evaluated to guarantee the viability of business model innovation. Paper 2 found that new business models are prone to fail if they are incompatible with end-users. For example adoption of service-based business models such as renting solar lanterns and batteries was reported to fail in a Zambian study due to customers’ preference for traditional cash sales models (Sloughter et al., 2016). Besides, business models were reported to fail due to factors such as perceived complex contract terms of service-based business models and incompatibility with customers' lifestyles (Barrie and Cruickshank, 2017). Customer engagement was out of the scope of the empirical study (Paper 3). Nonetheless, is a critical part of the EBuM framework because it determines whether customers will pay for new value propositions and, consequently, whether the environmental potential of the business model innovation scenario will be actualised in companies. The environmental benefits ultimately depend on the extent to which customers are receptive to service-based value propositions such as leasing and renting and retain the use of products over time. Burns (2010) found that preventing premature obsolescence may not be beneficial if customers abandon products for reasons such as switching to substitutes, functional, social, economic, aesthetical, or technological. For example, customers switching from tier 1 and 2 technologies like solar lanterns or solar home systems to tier 4 e.g., solar mini-grids. Another potential source of environmental burden is the extension of the national grid to off-grid areas to displace incumbent business models in line with national electrification master plans.

The EBuM framework is iterative, thus, if customers reject new value propositions as in the Zambian study, companies will be compelled to re-evaluate their approach to creating and delivering value which might have further implications on the magnitude of environmental impacts. The re-evaluation requires the involvement of customers in identifying new value propositions that are compatible with their lifestyles and preferences. Ideally, iterations should be performed to create business models that mitigate the environmental impacts, have a wide customer acceptance and adoption, and are commercially viable. The EBuM framework does not anticipate the impacts of phasing out business models e.g., in the event of grid extension in off-grid areas.

5.2 Implications for industry actors and policy-makers

This research provides evidence of the LCA of renewable energy in Africa and the social, economic, and environmental value of their business models. It also provides evidence of the effectiveness of business model innovation strategies in mitigating the environmental impacts of traditional business models. There are several key implications for companies (micro-level), industry (meso-level), and policy (macro-level).

5.2.1 Implication for business and industry actors

There is a need for (i) partnerships of key stakeholders throughout the life cycle of technologies, (ii) infrastructural (e.g., information technology) advancements must be accomplished in sectors that will have an impact on business model innovation, (iii) timely and reliable information flow among stakeholders, (iv) access to finance, and (v) societal acceptance of business model innovation. Uncertainties about the environmental performance of adopting circular business models occur if their financial viability is contingent on mass sales (Böckin et al., 2022). The financial viability of adopting circular business models in companies is affected by among other factors the availability of investment costs, the contractual terms of service-based agreements, and the familiarity with closed-loop recycling (Vermunt et al., 2019). Societal factors such as customers' attitudes, willingness-to-pay for new value propositions, awareness of environmental conservation, and perceived social values affect the success of circular business models (Mostaghel and Chirumalla., 2021; Kazeminia et al., 2016; Mentink, 2014).

Companies need to understand the current social, economic, and environmental sustainability context of their business models to pinpoint in which blocks innovation is required. Current business models determine the extent to which they must be modified to attain the intended benefits as shown in the case companies. At the micro- and meso-level, a key implication for companies is the need for collaboration with external actors along the renewable energy value chain. Disjointed activities in each section of the value chain where the manufacturers, developers and operators, and recyclers operate in isolation result in burden-shifting. Companies should create strategic partnerships with other industry actors to achieve a truly closed-loop system. These partnerships must allow for the transfer of contracts in the event of stakeholders changing their business models. For example, one of the companies was concerned about the implication of horizontal integration in the supply chain on take-back agreements.

Certain aspects of business model innovation rely on progress in other sectors at the meso-level to be feasible. For example, the rural-urban digital divide must first be bridged for solar energy companies to extend digitalisation services to their customers in rural areas. Investing in digitalisation infrastructure will create systems for advanced monitoring, fault diagnostics, and repair to slow resource loops. Monitoring and tracking renewable energy systems, including the small mobile solar home systems that are distributed over a wide geographical scope, makes it easier to keep valuable materials within the closed-loop system.

The success of closed-looped recycling rests on a predictable volume of waste entering the waste stream at a given time, reporting the physical condition of the waste, customer proximity to waste collection centres, waste collection frequencies at the micro-level, etc. It also requires proper electronic waste handling facilities at the meso-level. So far, there is an electronic waste challenge in many parts of Africa. Formal facilities such as the Waste Electrical and Electronic Equipment **(**WEEE) centre and the East Africa Compliant Recycling Company recover and recycle materials like aluminium and copper from electronic waste (CLASP et al., 2019). These facilities sell the recovered materials to local dealers, export what they cannot treat locally to Dubai and Belgium, and landfill residual waste (ibid). However, data on the capability and capacity of existing e-waste recycling facilities in Kenya is not always publicly available therefore it is difficult to estimate the volume of waste they can handle. The informal sector (i.e., *jua kali*), dominate electronic waste management in Kenya (Ministry of Environment and Forestry, 2019) and poses barriers to access waste by formal recyclers due to conflict over recyclable materials (Africa Clean Energy Technical Assistance Facility, 2019). Wilson et al. (2006) point out that setting up formal recycling facilities where informal recycling is prevalent may be counterproductive if informal recyclers are not integrated into the waste management process. Thus, building on the experience of the informal sector rather than substituting it, is necessary (Ezeah et al., 2013; Wilson et al., 2019).

The business model innovation pathway comprises sequential steps with key deliverables that must be financed to attain the environmental benefits. Schaltegger and Synnestvedt (2002) argue that in most organisations the decision to innovate business models is two-dimensional. Companies can either select the most favourable level of environmental performance that results in economic gains or the level that incurs the least cost while maintaining profitability. Often, companies choose environmental strategies that are cost-efficient before determining to what extent they implement them (ibid). Companies may rely on innovative financial instruments that accept the risk of market uncertainty of the business model innovation scenario (i.e., no track record) to unlock funding for innovation while maintaining economic success. Particularly so for the early- and growth-stage ventures that are classed in the missing middle category (i.e., they are too large for micro-finance or pilot capital and too small and risky for traditional lenders like commercial banks). So far, project-level debt and equity for small and medium-sized enterprises, commercial bank lending, and development finance from multilateral development institutions are unveiling CE finance globally (Ellen Macarthur Foundation, 2020).

Financial and societal factors are also important for customers when implementing new value propositions at the micro-level. Mitigating environmental impacts can come at a cost to the company and customers. Customers' willingness to accept changes to their offering may be motivated by the financial terms. Besides monetary reasons, Paper 2 showed that new business models tend to fail when they are disconnected from customers' mainly due to preferences, incompatibility with customers' lifestyles, and complex contracts. Depending on the business model, understanding marketplace considerations based on the interest of individual customers and the market as a whole is necessary for harnessing customer relationships that add value to the new value propositions. For example, a product or service offering can be tailored both to individual customers' ability to pay for energy needs and to the general requirements of the market (e.g., energy access).

5.2.2 Implications for policy

This research has three main implications for policymakers that can directly or indirectly be derived from this study. Firstly, the transition to circular business models will require an enabling environment (e.g., policy and regulations) that incentivises companies to innovate. Secondly, there is a need for private-public partnerships that support infrastructural projects for the end-of-life. Thirdly, institutional support is necessary to create markets for CE initiatives.

Policy and regulatory support at the macro-level will be required to create an enabling environment for business model innovation to achieve the stated benefits of circular business models (Paper 3). CE is increasingly being accepted by policymakers as the preferred development paradigm that has the potential to yield environmental, social, and economic benefits (Ellen MacArthur Foundation et al., 2015; Preston et al., 2019). However, the linear economy model is still predominant in Africa due to scarce macroeconomic tools for modelling and implementing the transition to CE (Preston et al., 2019). These tools are available in countries like Libya, Algeria, South Africa, Angola, Nigeria, and Gabon (ibid; McCarthy et al., 2018). At the time of this research, Kenya had put in place the extended producer responsibility regulation to promote CE (Ministry of Environment and Forestry, 2020). However, business models were still predominantly linear-economy-oriented due to the absence of key institutions that support the actualisation of CE.

Policy and governance support is also required in designing specialised infrastructure for the end-of-life to solve the imminent waste challenge. Special facilities (e.g., sanitary landfills, inert material landfills, residual waste landfills, incinerators with energy recovery, and recycling facilities) are needed for the treatment or conversion of different types of renewable energy waste. Paper 2 shows that renewable energy projects can be implemented through private-public partnerships models such as build-operate-transfer or build-own-operate. Such partnerships are critical for waste management and can unlock private sector funding and attract technical expertise. They can also build the capacity of renewable energy companies, their customers, partners, and stakeholders to contribute more effectively to circular business models.

Besides private-sector finance, there is also a need for public-sector institutional support to access funds and create competitive markets for emerging circular business models. Paper 2 calls attention to the notion that the risk of doing business in African countries is high due to high capital costs, high-interest rates on loans, and market immaturity in terms of subsidies or tax breaks. These issues can affect the business case and bankability of the emerging circular business models.

5.3 Overall contribution to wider literature and research impact

This research has three main contributions. First, Paper 1 in Chapter 2 broadens the analysis of the environmental impacts of renewable energy in Africa by synthesising papers on LCA to highlight the status of research, methodological issues and their implications on the robustness of the results, and research needs for the continent. Paper 1 provides insights into the requirements and best practices for LCA studies following ISO 14040 and 14044 (ISO 2006a, b) guidelines. Consequently, the findings of Paper 1 not only improve the understanding of the environmental impacts of varied renewable energy sources on the continent but also the research challenges and gaps that practitioners and decision-makers should take heed of.

Second, Paper 2 provides synthesised empirical evidence that highlights the needs of Africa's renewable energy sector and to what extent incumbent business models satisfy the criteria of social, economic, and environmental sustainability. This Paper performs an in-depth analysis of the status quo of business models to identify drivers and barriers to their viability in the region. It increases the understanding of why renewable energy business models in Africa fail or succeed drawing insights from a broad range of cases implemented across the continent. The cases present evidence from across the continent and key lessons learned that can be beneficial to businesses and policymakers in Africa.

Third, Paper 3 creates the EBuM analytical framework that can be used to perform the LCA of business models through stakeholder engagement (Chapter 4). The framework integrates the LCA methodology (ISO, 2006a,b), business model innovation, and participatory decision-making (Kaner et al., 2014). The framework can be applied to businesses across different sectors to improve the understanding of how business models contribute to environmental impacts and, conversely, their potential in mitigating the impacts. It applies LCA to quantify stakeholders' decisions and allows the comparison of new business models relative to the baseline case. The framework can be expanded to accommodate a more holistic approach that includes life cycle costs and social assessments although this analysis is beyond the scope of this study

From Paper 1 it is apparent that previous studies performed LCAs of renewable energy in Africa, focusing on the technology but excluded the business models in which they are implemented. Paper 2 shows that studies prioritised social and economic dimensions of business models but excluded environmental sustainability in the assessments. LCA and business models are two different fields that are well researched (see Paper 1 and Paper 2). When these two fields are paired, they present a nascent area of research. At the time of this study, there was no peer-reviewed research on LCA of business models in Africa, particularly for the renewable energy sector. Paper 3 is the first attempt at addressing this research gap. It contributes to the growing body of knowledge by applying the analytical framework to solar energy companies. The application of the framework shows how stakeholders' decisions can be incorporated into the design of circular business models that potentially have better environmental performance than their substitutes. Paper 3 makes the initial attempts to bridge the knowledge gap between LCA and business models literature.

The three papers are interconnected and have significant implications for research, industry, and policy. They present the potential and challenges of attaining environmental sustainability in Africa's renewable energy sector. The challenges which range from methodological issues to unexplored subject matters must be resolved to perform more comprehensive and holistic sustainability assessments for decision-making.

Chapter 6: Research limitations, future research, and conclusions

This chapter gives the limitations of this research, recommendations for future work, and concluding remarks.

6.1 Research limitations

The limitations of this research are primarily scope-related. The keyword search and exclusion criteria of Paper 1 and 2 may omit significant literature from the sample, thus, potentially excluding important findings and affecting the recommendations. For example, the exclusion of research published in grey literature and studies not published in English may create concern about publication bias. Likewise, the keyword combination and synonyms applied to titles and abstracts potentially exclude studies on the topic that do not use the selected terminology. Studies outside the energy research discipline (e.g., rural development, urban planning, anthropology which address social, economic, and environmental sustainability of renewable energy) may also have been excluded. The systematic literature reviews aimed to be thorough and generalise findings on the topic. However, the probable exclusion of studies makes it non-exhaustive and may leave out key studies that may change the findings of the analysis.

A major limitation of LCA is the absence of geographical representativeness of life cycle inventory databases and technical limitations of the impact assessment method. So far, only a few datasets that are specific to Africa are included in generic databases like Ecoinvent which was created for North American and Western European contexts. There are currently no national or regional life cycle inventory databases for Africa, thus, LCA practitioners rely mostly on global averages included in generic databases to model inventories. Adapting such databases to the African context is still associated with some degree of uncertainty due to data gaps which may affect the accuracy of LCA results, particularly for regional and local impact categories. Most impact assessment methods are not only limited in their geographical coverage but also associated with uncertainties in spatial variation (Bulle et al., 2019). A majority of these methods such as Eco-indicator 99, EDIP, EPS, ReCiPe, and Impact 2002+

were developed for the Western European region while LIME, LUCAS, and TRACI were developed for Japan, Canada, and the USA, respectively (ibid). Using generic characterisation factors of these impact assessment methods to model global averages for the African context creates uncertainties due to spatial variability of impacts. Emissions at the regional and local scale are affected by sensitivities of ecosystems, thus, there is a need for accurate spatial information when calculating the impacts of environments with different sensitivities (Reap et al., 2008). This need calls for global regionalised impact assessment methods to address spatial (European Commission, 2010) such as the IMPACT World+ whose characterization factors assess impacts at the global, continental, country, and local levels (Bulle et al. (2019).

There are several limitations of Paper 3 that may affect the LCA results. Firstly, only the environmental impacts of electricity generation from solar PV systems are quantified. For dual fuel hybrid systems like mini-grids which are coupled by fossil diesel generators, only PV generation is considered because of different input requirements for energy conversion. Secondly, the distribution of electricity to the customer segments is not considered; hence, the LCA of the transmission and distribution grid is not performed. Thirdly, where site-specific and system-specific data are missing, generic data from Ecoinvent version 3.5 are used and adapted to the local context. Fourthly, modelling assumptions made in the inventory affect the LCA results. For example, assumptions about the transport vessel (i.e., EURO 3, 1 to 32 metric ton truck) were based on the fuel quality in several countries in Africa (Ayetor et al., 2021; UNEP, 2020). Assumptions were also made about the recycling efficiencies in the business model innovation scenario to show the best case based on literature values (e.g., Latunussa et al., 2016). These assumptions were only made when specific data were missing. Transport impacts are less sensitive to the final results because they are negligible (i.e <10%). Conversely, end-of-life impacts are not insignificant. For example in the business model innovation scenario in Chapter 4 (section 4.2.2.3.2), assuming high recycling rates in the FRELP process displaces significant amounts of emissions in the manufacturing processes (e.g., climate change potential reduces by 24%-63%). Different end-of-life assumptions e.g., reusing, recycling, and repurposing may substantially affect the results. These limitations could create uncertainty in the robustness of LCA results. Such uncertainties could potentially affect decision-making especially if the assumptions change significantly or cannot be agreed on by decision-makers.

Fifthly, the EBuM framework has been tested on four business models implemented in Kenya (i.e., rent-to-own, prosumer, EPC with leasing, and pay-per-service unit). Other types of business models for solar energy identified in the systematic literature review (e.g., EPC for utility-side systems, swarm electrification, renting, and leasing) have not been evaluated, thus, creating an empirical limitation of this study. Business models for non-solar PV renewable energy systems are also excluded. The EBuM framework comprises steps for evaluating the environmental impacts of business models considering social and financial aspects. The empirical research (Paper 3) limited its analysis to the environmental sustainability of business models which was a research gap identified in the systematic literature reviews. The recommended circular business models (e.g., switching from product sales to providing solar as a service) have neither been tested among end-users nor from a financial perspective. Thus, the extent to which environmental impacts will be affected by the outcomes of the customer engagement and financial assessment is unknown. Companies may be required to re-evaluate their business model innovation recommendations to address end-user needs and preferences should they reject the new value propositions.

The empirical study also relies on product life extension to mitigate the life cycle impacts associated with each business model. It does not consider obsolescence that may occur during the use stage of products e.g., customers abandoning low-tier technologies such as DC solar home systems due to their limited functionality in preference for high-tier AC systems such as solar mini-grids. Although the empirical study provides a comprehensive assessment of the business models, the rebound effects of business model innovation are not calculated because this analysis was out of the scope of this research. Rebound effects may come about as a result of system boundary definition and can create undesired environmental outcomes (Sorrell, 2007). They are not easy to quantify and highly variable depending on local conditions (Warmington-Lundström and Laurenti, 2020).

6.2 Future work

Several recommendations for future work are identified based on the three papers as follows:

6.2.1 LCA of renewable energy

Current studies have covered LCAs of solar PV and first-generation bioenergy to a great extent (Chapter 2; Paper 1). LCAs of wind turbines and hydropower are covered to a lesser extent while other renewable energy sources and technologies (e.g., geothermal) are unresearched. This research discusses the relevance of assessing the environmental impacts of renewable energy in Africa in light of the growth of the sector. Future research work should investigate the unresearched and under-researched renewable energy technologies to provide an understanding of their environmental sustainability. Other unexplored areas in LCA research as identified in Paper 1 are the end-of-life of renewable energy technologies and non-climate change impact categories. The end-of-life is particularly important for Africa considering the continent may account for most new additions in installed capacity by 2030 (IRENA, 2019). Thus, it should be investigated taking into account the waste challenge of increasing the diffusion of renewable energy technologies. Research efforts should also focus on complete coverage of impact categories to fully understand the consequences of renewable energy development and reduce burden-shifting during decision-making.

6.2.2. Business models of renewable energy

The environmental sustainability of incumbent renewable energy business models in Africa is missing in research (Chapter 3; Paper 2). Paper 3 in Chapter 4 addresses this gap focusing on solar PV but there is scope to investigate business models for other renewable energy sources and sectors using the generic EBuM framework. The social and economic dimensions of business models are key drivers of renewable energy growth in Africa so far. Taking a closer look at the environmental implications of these dimensions can be beneficial to businesses and policymakers.

6.2.3 Economic and social analysis of circular business models

Studies on LCA of renewable energy business models are scarce. Paper 3 is among the few studies that use LCA to analyse renewable energy through the lens of business models. The scope of this study limits the analysis to the environmental dimension of business models.

However, the benefits of transitioning to CE discussed in Paper 3 can only be actualised by considering the social and financial dimensions of business model innovation. Oliveira (2017) states that adopting circular business models can incur high investment costs from financing asset ownership and longer cashflow cycles as revenue shifts from sales to leasing, hence, low returns on assets in the short-term. However, the revenue increases and stabilises in the long-term because of product life extension (ibid). Barriers to financing infrastructural investment e.g recycling facilities affect the ability of companies to innovate. There is a wide financing gap for clean energy transition (IRENA, 2020) and CE financing needs outweigh the funds made available through traditional lending or money firms set aside for research and innovation (Lacy et al., 2020). Future studies can investigate these issues in detail.

Another area of future research focus is quantifying rebound effects of business model innovation which are bound to occur but have not been investigated in Paper 3. While the emphasis in section 6.2.1 is the environmental sustainability of renewable energy technologies, the recommendation for this section goes further to draw attention to the social and economic aspects that influence how well environmental sustainability is achieved.

In summary, the main conclusions of this research are:

- Renewable energy development in Africa is associated with significant environmental impacts. However, the absence of databases created for the African contexts and the use of global averages affect the representativeness of the findings.
- The climate change potential of renewable energy is researched to a considerable extent in LCA studies, unlike other impact categories. Likewise, LCAs that evaluate the end-of-life of renewable energy are scarce. To avoid the issue of burden-shifting, all life cycle stages and impact categories should be considered. The implication of ommissions on the LCA results should be adequately discussed.
- Incumbent business models for renewable energy in Africa focus more on creating and delivering social and economic value and less on environmental sustainability on a life cycle basis.
- The EBuM framework can be used to analyse the environmental impact of business models in different sectors.
- Business models are drivers of environmental impacts but have a considerable potential to mitigate them through business model innovation.

- The environmental impacts of traditional business models of solar energy in Kenya can be mitigated by adopting CE principles. However, these outcomes may vary on a case-by-case basis, hence, LCA must be used to assess the consequences of adopting them. Besides, the traditional business models in this study (Paper 3) are commonly adopted in Africa, therefore, the findings and recommendations of this study can be adopted by developers, distributors, and system operators on the continent.

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Supporting information Paper 1: Life Cycle Assessment of Renewable Energy in Africa

Table A 1: Keyword search and search results in Scopus and Web of Science for LCA of renewable energy in Africa

Search strings	**Search results**	**Relevance to topic**	
		Included	**Excluded**
“Life Cycle Assessment” AND “renewable energy” AND “Africa”	35	20	15
“Life Cycle Assessment” AND “renewable energy” AND “name of an African country"	89	33	56
“Life Cycle Assessment” AND “renewable energy” AND “developing countries”	33	0	33

Table A 2: Overview of the functional units, technology application, system boundary and life cycle inventory

Reference	**Country**	**Technology / application**	**Goal and Scope definition**	**Functional unit**[a]	**System Boundary**		**LCA Software**	**Database**	**Foreground LCI data**	**Multifunctionality**	**Impact assessment method**	**Impact category/other category**	**Normalis-ation**	**Uncetainty analysis**
					Boundary	**Capital goods** [b]								
Ramjeawon, T. (2008). 'Life cycle assessment of electricity generation from bagasse in Mauritius', *J. Clean. Prod*., 16(16), 1727-1734. Available at: https://doi.org/10.1016/j.jclepro.2007.11.001	Mauritius	Bioenergy-bagasse/solid biofuel/ power generation	To assess the environmental burden of power generation from bagasse, identify opportunities for impact reduction, and compare the impacts to the electricity mix of Mauritius.	1 GWh of electricity	Production (cane production, burning, harvesting), production of fertilisers, transport, processing sugarcane, electricity generation.	Excluded	SimaPro	Not specified	Secondary data	Allocation by economic value	CML World 1992, Eco-indicator 99 endpoint:	GWP, ODP, HTP, EP, AP, ecotoxicity, smog HH, ecosystem quality, resources Other: NER	Not performed	Not performed
Mbohwa, C. and Myaka, N. (2010). Social life cycle assessment of biodiesel in South Africa: an initial assessment, The 9th International Confeence on Ecobalance, Tokyo 2010. Available at: http://hdl.handle.net/10210/14434	South Africa	Bioenergy-soybean biodiesel/ liquid biofuel/ transport	To assess social life cycle impacts of biodiesel production in South Africa	Not defined	Not defined	Excluded	Not specified	Not specified	Not specified	Not performed	Not specified	Not specified	Not performed	Not performed
Brent, A., Sigamoney, R., von Blottnitz, H. and Hietkamp, S. (2010). 'Life cycle inventories to assess value chains in the South African biofuels industry', *J. Energy South Afr*., 21(4), 15-25. Available at: http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-447X2010000400003	South Africa	Bioenergy-soybean, sunflower, canola biodiesel/liquid biofuel/ transport	To compile a life cycle inventory of liquid biofuels.	19.5 kt/year of biodiesel (reference flow)	Biodiesel production only.	Excluded	Not specified	Free databases (not explicit)	Primary and secondary data	n/a (LCI of biodiesel)	Not applicable	Not applicable	Not applicable	Not applicable

Achten, J., Vandenbempt, P., Almeida, J., Mathijs, E. and Muys, B. (2010). 'Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in Cameroon', *Environ. Sci. Technol*., 44(12), 4809-4815. Available at: https//doi.org/10.1021/es100067p	Cameroon	Bioenergy- palm oil/ liquid biofuel/ transport	LCA for the production and use of palm oil for cooking and biodiesel.	1 MJ in car engine	Production (crop cultivation), processing (extraction and refining), biodiesel production, transport, and infrastructure maintenance.	Not specified	Not specified	Not specified, secondary sources used	Primary and secondary	System boundary expansion	IPCC, Nordic guidelines on LCA	FDP, NER, GWP, EP, AP LUP, CPBT	Not performed	Monte Carlo uncertainty analysis
Gujba, H., Mulugetta, Y. and Azapagic, A. (2010). 'Environmental and economic appraisal of power generation capacity expansion plan in Nigeria', *Energy Policy*, 38(10), 5636-5652. Available at: https://doi.org/10.1016/j.enpol.2010.05.011	Nigeria	Electricity mix- gas, coal, hydro, biomass, wind, solar PV, solar thermal/ power generation	LCA and economic assessment of Nigeria's present and future electricity generation.	Functional units expressed as MWh/year between 2003 and 2030	Production, transport, and use.	Included	SimaPro 6 and GEMIS version 4.3	GEMIS 4.3	Primary and secondary data	Not performed	CML 2001	GWP, AD, ODP, HTP, FETP, METP, TETP, POFP, AP, EP	Not performed	Not performed
Espinosa, N., García-Valverde, R. and Krebs, C. (2011). 'Life-cycle analysis of product integrated polymer solar cells', *Energy and Environ*. Sci., 4(5), 1547-1557. Available at: https//doi.ord/10.1039/C1EE01127H	Ethiopia	Solar- organic solar PV, lithium polymer battery/ power generation	Quantification of energy use and identification of hotspots to reduce the environmental impacts of an organic solar lamp through eco-design.	1 hour of daily operations in a year, 104 cm^2 lamp	Production, transport, use, and landfill.	Included	Not specified, equations used	Free databases (not explicit)	Secondary data	Not performed	Not specified	GWP, CED, EPBT, CPBT	Not performed	Not performed
Viebahn, P., Lechon, Y. and Trieb, F. (2011). 'The potential role of concentrated solar power (CSP) in Africa and Europe-a dynamic assessment of technology development, cost development and life cycle inventories until	Algeria	Solar- concentrated solar power; BoS (thermal storage)/ power generation	To calculate life cycle inventories of existing and proposed power plants and update the LCI to scenarios in 2025 and 2050.	1 kWh of electricity generated	Production, transport, use, and dismantling.	Included	Not specified	Not specified	Secondary data	Not performed	IPCC	GWP	Not performed	Not performed

2050', *Energy Policy*, 39(8), 4420-4430. Available at: https://doi.org/10.1016/j.enpol.2010.09.026														
Afrane, G. and Ntiamoah, A. (2011). 'Comparative life cycle assessment of charcoal, biogas, and liquefied petroleum gas as cooking fuels in Ghana', *J. Ind. Ecol*., 15(4), 539-549. Available at: https://doi.org/10.1111/j.1530-9290.2011.00350.x	Ghana	Bioenergy-biogas; charcoal; LPG/ thermal	LCA to assess the environmental impacts of biogas, charcoal, and liquefied petroleum gas in Ghana.	1 MJ of fuel produced by each fuel	Biogas: collection of raw materials/dung (production excluded), operation of biogas plant, use of biogas, disposal of digestate on farm as fertilizers Charcoal: wood carbonization, transport, utilisation	Biogas: excluded	GaBi	GaBi and Ecoinvent	Primary and secondary data	Allocation: not explicitly defined	CML	AP, EP, FETP, GWP, HTP, POFP, TETP	Not performed	Not performed
Andrae, G., Han, D., Luo, S., Belfqih, M. and Gerber, E. (2012). Added value of life cycle assessment to a business case analysis of a photovoltaic/wind radio base site solution in South Africa, IEEE International Telecommunications Energy Conference, Scottsdale 2012. Available at: https://doi.org/10.1109/INTLEC.2012.6374478	South Africa	Solar and wind- wind turbine and solar PV, lead-acid battery/ power generation	To quantify CO2 emissions from a new site comprising a solar PV/ wind turbine system and compare it with a traditional site that is powered by a diesel generator.	Electricity delivery for 10 years	Production, transport, use, and recycling.	Included	Not specified, equations used	Not specified	Primary data	Not performed	ReCiPe midpoint	GWP, CED, ODP, HTP, POFP, PMFP, IRP, TAP, FEP, MEP, TETP, METP, LUP, WDP, MDP, FDP, EPBT, CPBT, FPBT	Not performed	Not performed

Dufo-López, R., Zubi, G. and Fracastoro, G. V. (2012). 'Tecno-economic assessment of an off-grid PV-powered community kitchen for developing regions', *Appl. Energy*, 91(1), 255-262. Available at: https://doi.org/10.1016/j.apenergy.2011.09.027	Nigeria, Pakistan, Bangladesh, India, Indonesia	Solar-multicrystalline solar PV, lead-acid battery, inverter/ powr generation	LCA to identify the potential of combining a hybrid solar PV system with electric cooking appliances in a community of 50 people.	Electricity use per meal (*not explicitly defined*)	Production, transport, use, and decommission.	Included	Not specified	Not specified	Secondary data	Not performed	Not specified	GWP, EPBT	Not performed	Not performed
Nzila, C., Dewulf, J., Spanjers, H., Tuigong, D., Kiriamiti, H. and van Langenhove, H. (2012). 'Multi criteria sustainability assessment of biogas production in Kenya', *Appl. Energy*, 93, 496-506. Available at: https://doi.org/10.1016/j.apenergy.2011.12.020	Kenya	Bioenergy-floating drum digester, fixed dome digester, inflatable tubular digester/ biogas/ thermal	To perform LCA of a floating drum, fixed dome and tubular digester biogas technologies in order to identify the best technology option	1m^3 of biogas	Digester: production of raw materials, construction, use, and end-of-life Biogas: production of feedstock, use of energy, end-of-life disposal of digestate	Included	SimaPro	Ecoinvent 2.2	Primary and secondary data	Not performed	CEENE, IPCC, CED	MDP, GWP, CED , EPBT	Not performed	Not performed
Almeida, J., Achten, W., Duarte, M., Mendes, B. and Muys, B. (2011). 'Benchmarking the environmental performance of jatropha biodiesel systems through a generic life cycle assessment', Environ. Sci. Technol., 45, 5547-5453. Available at: https://doi.org/dx.doi.org/10.1021/es200257m	Tanzania	Bioenergy-jatropha/liquid biofuel / transport	To perform a life cycle of biodiesel production from jatropha.	1 MJ of biodiesel produced and delivered	Cultivation and oil extraction, transport, biodiesel production and use.	Included	SimaPro	Ecoinvent, BUWAL 250, ETH-ESU 96	Primary and secondary data	System boundary expansion	Impact 2002+	GWP, FDP, ODP, EP, AP	Not performed	Sensitivity analysis

Afrane, G. and Ntiamoah, A. (2012). 'Analysis of the life-cycle costs and environmental impacts of cooking fuels used in Ghana', *Appl. Energy*, 98, 301-306. Available at: https://doi.org/10.1016/j.apenergy.2012.03.041	Ghana	Energy mix-biogas, hydropower, firewood, kerosene, LPG/ thermal	To compare the environmental impacts of fuel used for cooking in households: firewood, kerosene, charcoal, LPG, electricity and biogas.	1 MJ of energy delivered to the cooking pot	Use	Hydropower : excluded	Not specified	Ecoinvent and GaBi	Secondary data	Not performed	CML 2001	GWP, AP, FETP, POFP, HTP, TETP	Not performed	Not performed
Felix, M. and Gheewala, S. H. (2012). 'Environmental assessment of electricity production in Tanzania', *Energy Sustain. Dev.,* 16(4), 439-447. Available at: https://doi.org/10.1016/j.esd.2012.07.006	Tanzania	Hydropower and fossil fuels/ power generation	LCA of electricity generation from hydropower natural gas, coal, heavy fuel oil and industrial diesel in Tanzania for 2000, 2015, 2020, 2026 and 2030.	1 MWh of electricity	Production (construction of hydropower plants) and use.	Included	SimaPro 7.3.3	Ecoinvent 2.2 and US life cycle inventory 1.6.0	Primary and secondary data	Not performed	CML 2001	ADP, GWP, AP, EP	Not performed	Not performed
Eshton, B., Katima, Y. and Kituyi, E. (2013). 'Greenhouse gas emissions and energy balances of jatropha biodiesel as an alternative fuel in Tanzania', *Biomass Bioenergy*, 58, 95-103. Availale at: https://doi.org/10.1016/j.biombioe.2013.08.020	Tanzania	Bioenergy-jatropha/liquid biofuel/ power generation and transport	LCA of net greenhouse gas emissions of jatropha biodiesel production and use as an alternative to fossil diesel.	1 tonne of combusted jatropha biodiesel	Feedstock: cultivation, processing and biodiesel production, and biodiesel use.	Excluded	Not specified, equations used	Ecoinvent	Primary and secondary data	Allocation by content	Not specified	GWP, NEV, NREV	Not performed	Not performed

Hagman, J., Nerentorp, M., Arvidsson, R. and Molander, S. (2013). 'Do biofuels require more water than do fossil fuels? Life cycle-based assessment of jatropha oil production in rural Mozambique', *J. Clean. Prod.*, 53, 176-185. Available at: https://doi.org/10.1016/j.jclepro.2013.03.039	Mozambique	Bioenergy-jatropha oil/liquid biofuel/thermal	LCA of oil production from jatropha compared to fossil diesel.	1 MJ of fuel in formof jatropha oil	Feedstock: cultivation, processing, and use.	Included	Not specified, equations used	Not specified	Primary and secondary data	Not performed	IPCC	GWP, WDP	Not performed	Performed (analysis method not specified)
Mashoko, L., Mbohwa, C. and Thomas, V. M. (2013). 'Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry', *J. Clean. Prod.*, 39, 42-49. Available at: https://doi.org/10.1016/j.jclepro.2012.08.034	South Africa	Bioenergy-bagasse/ solid biofuel/ power generation	To identify processes that contribute to the inventory of South Africa's electricity generation from bagasse and to compare the inventory to that of electricity generation from coal.	1 GWh of electricity in South Africa sugar industry	Feedstock cultivation, processing, and electricity generation	Excluded	SimaPro	Ecoinvent	Primary and secondary data	Allocation by economic value	IPCC	NER, CED, GWP	Not performed	Not performed
Andrianaivo, L. and Ramasiarinoro, J. (2014). 'Life cycle assessment and environmental impact evaluation of the parabolic solar cooker SK14 in Madagascar', *J. Clean Energy Technol.*, 2(2), 191-195. Available at: https//doi.org/10.7763/JOCET.2014.V2.121	Madagascar	Solar-parabolic solar/ thermal	To compile an inventory of the life cycle impacts associated with parabolic solar, firewood, and charcoal and to use the inventory data to perform LCA of parabolic solar cooker.	MJ per meal	Production and use.	Included	Not specified, equations used	Not specified	Primary and secondary data	Not performed	Not specified	GWP, CED	Not performed	Not performed

Ekeh, O., Fangmeier, A. and Müller, J. (2014). 'Quantifying greenhouse gases from the production, transportation and utilization of charcoal in developing countries: a case study of Kampala, Uganda', *Int. J. Life Cycle Assess*., 19(9), 1643-1652. Available at: https//doi.org/10.1007/s11367-014-0765-7	Uganda	Bioenergy-charcoal/ solid biofuel/ thermal	To quantify greenhouse emission from charcoal production, transportation and utilisation.	1 kg of charcoal	Feedstock production, transport, and use.	Not specified	GaBi 4.0	Not specified, secondary sources used	Primary and secondary data	Not performed	CML 2001	GWP	Not performed	Monte Carlo uncertainty analysis
von Doderer, C. and Kleynhans, T. E. (2014). 'Determining the most sustainable lignocellulosic bioenergy system following a case study approach', *Biomass Bioenergy*, 70, 273-286. Available at: https://doi.org/10.1016/j.biombioe.2014.08.014	South Africa	Bioenergy-lignocellulosic biomass/solid biofuel / power generation	To determine suitable lignocellulosic bioenergy systems based on the least environmental impact and compare it to South Africa's energy mix.	Annual electricity generated over 330 days of full production	Feedstock production, transport, processing, and energy generation.	Included	Not specified	GaBi 4.4	Secondary data	Not performed	CML 2001	GWP, AD, AP, EP, POFP,	Performed	Not performed
Almeida, J., Moonen, P., Soto, I., Achten, J. and Muys, B. (2014). 'Effect of farming system and yield in the life cycle assessment of Jatropha-based bioenergy in Mali', *Energy Sustain. Dev*., 23, 258-265. Available at: https://doi.org/10.1016/j.esd.2014.10.001	Mali	Bioenergy-jatropha/ liquid biofuel/ power generation	To quantify GHG emissions and primary energy demand and efficiency of jatropha biodiesel production and use.	1 MJ of electricity	Feedstock production, transport, processing, and energy generation.	Excluded	SimaPro	Ecoinvent 2.2	Primary and secondary data	System boundary expansion	Not specified	GWP, FDP, CED	Not performed	Not performed

Galgani, P., van der Voet, E. and Korevaar, G. (2014). 'Composting, anaerobic digestion and biochar production in Ghana. Environmental-economic assessment in the context of voluntary carbon markets', *Waste Manage*., 34(12), 2454-2465. Available at: https://doi.org/10.1016/j.wasman.2014.07.027	Ghana	Bioenergy-biogas/gaseous biofuel/ power generation	LCA and economic viability assessment of anaerobic digestion, composting, and biochar production in Ghana.	Generation of 301.7 MWh for a period of 1 year, disposal of 1500 t of organic waste and 2500 t of rice husks, and Fertilisation of 2300 ha of land	Production of capital goods, feedstock production, processing, and electricity generation.	Included	Not specified	Ecoinvent	Secondary data	Not performed	Not specified	GWP	Not performed	Done (analysis method not specified)
Njenga, M., Karanja, N., Karlsson, H., Jamnadass, R., Iiyama, M., Kithinji, J. and Sundberg, C. (2014). 'Additional cooking fuel supply and reduced global warming potential from recycling charcoal dust into charcoal briquette in Kenya', *J. Clean. Prod*., 81, 81-88. Available at: https://doi.org/10.1016/j.jclepro.2014.06.002	Kenya	Bioenergy-charcoal/solid biofuel / thermal	To quantify GWP along the life-cycle stages of charcoal briquette and identify stages for policy and technology intervention.	Fuel use in meal preparation for five people	Feedstock production, processing, transport, and recycling of charcoal dust into briquettes.	Not specified	SimaPro 7.33	Ecoinvent	Primary and secondary data	Not performed	Not specified	GWP, LUP, MDP	Not performed	Not performed
Al-Behadili, H. and El-Osta, B. (2015). 'Life Cycle Assessment of Dernah (Libya) wind farm', *Renew. Energy*, 83, 1227-1233. Available at: https://doi.org/10.1016/j.renene.2015.05.041	Libya	Wind- wind turbine/ power generation	LCA of a wind farm in Libya to determine the benefits of wind energy.	1 kWh of electricity generated	Production, transport, use, landfill	Included	Not specified, equations used	Not specified	Primary data	Not performed	IPCC 2006	GWP, EPBT, ER, CED	Not performed	Not performed

Onabanjo, T. and Lorenzo, D. (2015). Energy efficiency and environmental life cycle assessment of jatropha for energy in Nigeria: a "well-to-wheel" perspective, ASME 2015 9th International Conference on Energy Sustainability, Sandiego. 28th June-2nd July 2015. Available at: https://doi.org/10.1115/ES2015-49654	Nigeria	Bioenergy-jatropha/liquid biofuel/ power generation	LCA and energy efficiency of jatropha biodiesel in a 126 MW gas turbine plant.	1 MJ of fuel use in biodiesel plant	Feedstock production, processing, and energy generation.	Included	SimaPro	Ecoinvent and Agrifood	Primary and secondary data	Allocation by mass	IPCC and ReCiPe midpoint	GWP, ODP, POFP, FEP, MEP, TETP, FETP, AP, METP, IRP, PMFP, FDP NER, NEV, NREV	Performed	Not performed
Chinongo, T. and Mbohwa, C. (2015). 'Life cycle assessmsnt to assess and analyse bio-diesel production in South Africa,' *Conference Proceedings,* 1-4. Available at: http://hdl.handle.net/10210/72130	South Africa	Bioenergy-sunflower, canola, soybean/liquid biofuel/ application not explicitly defined	Social LCA, inventory for biofuel production (not explicitly defined)	19.5 kt/year of biodiesel	Production of biodiesel	Excluded	Not specified	Not specified	Primary and secondary data	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Brizmohun, R., Ramjeawon, T. and Azapagic, A. (2015). 'Life cycle assessment of electricity generation in Mauritius', *J. Clean. Prod.*, 106, 565-575. Available at: https://doi.org/10.1016/j.jclepro.2014.11.033	Mauritius	Bioenergy and hydropower-bagasse and hydropower/ power generation	To calculate the life cycle of electricity generation from coal, bagasse, fuel oil, and hydropower.	1 MWh of electricity	Production of fuels, feedstock, transport processing, electricity generation and transmission, waste treatment decommissioning.	Oil, coal and baggase plants-excluded	SimaPro	Ecoinvent	Primary and secondary data	Allocation by economic value	CML 2001	GWP, ADP, AP, EP, HTP, FETP, METP, ODP, POFP, TETP	Not performed	Not performed
Ito, M., Lespinats, S., Merten, J., Malbranche, P. and Kurokawa, K. (2016). 'Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world', *Prog. Photovol*., 24(2), 159-174. Available at:	Morocco and France	Solar- solar PV/ power generation	To determine GHG emissions and EPBT from a large scale-PV system and to develop a GHG map that can be used by decision makers to identify	1 kWh for PV; 1 MWh for system components	Production, transport, use, and landfill.	Included	SimaPro 7.3.3 and equations	Ecoinvent 2.2	Primary and secondary data	Not performed	Not specified	GWP, EPBT	Not performed	Not performed

https://doi.org/10.1002/pip.2650.			suitable locations for PV systems.											
Fawzy, M. and Romagnoli, F. (2016). Environmental life cycle assessment for jatropha biodiesel in Egypt, International Scientific Conference Environmental and Climate Technologies CONNECT 2015. 2016, Latvia. 4-6 October. pp. 124-131. Available at: https://doi.org/10.1016/j.egypro.2016.09.033.	Egypt	Bioenergy-jatropha/liquid biofuel/ transport	To analyse the environmental performance of biodiesel production from *jatropha platyphylla.*	1 tonne of biodiesel produced and used by average vehicle	Feedstock production, transport, processing, and energy generation.	Included	SimaPro	Ecoinvent	Primary and secondary data	System boundary expansion	Impact 2002+	Midpoint: EP, GWP, AP, ODP, IRP, MDP, LUP, TETP, AETP, HTP, HTNP, FDP Endpoint impacts: LOB, HH, CC, ecosystem quality, resources.	Not performed	Not performed
Almeida, J., De Meyer, A., Cattrysse, D., Van Orshoven, J., Achten, J. and Muys, B. (2016). 'Spatial optimization of jatropha based electricity value chains including the effect of emissions from land use change', *Biomass and Bioenergy*, 90, 218-229. Available at: https://doi.org/10.1016/j.biombioe.2016.04.010.	Mali	Bioenergy-jatropha/ liquid biofuel/ power generation	To design a method for LCA of electricity generation from jatropha and apply it to optimise the value chain to lower GWP.	1 kWh	Feedstock production, transport, processing, and energy generation.	Included	SimaPro	Ecoinvent	Primary and secondary data	Substitution: substituting production of fertiliser with seed cake	ReCiPe	GWP	Not performed	Uncertainties identified (uncertainty analysis not performed)
Almeida, J., Degerickx, J., Achten, J. & Muys, B. (2015). 'Greenhouse gas emission timing in life cycle assessment and the global warming potential of perennial energy	Mali	Bioenergy-jatropha/liquid biofuel/power generation	Analysis of dynamic LCA for perennial jatropha plantations.	1 MJ/year of electricity produced by a generator	Feedstock production, transport, processing, and energy generation.	Included	SimaPro	Ecoinvent	Primary and secondary data	System boundary expansion	IPCC and Dynamic LCA	GWP, EPBT	Not performed	Not performed

crops', *Carbon Manag*, 6(5-6), 185-195. Available at: https://doi.org/10.1080/17583004.2015.1109179.														
Bilich, A., Langham, K., Geyer, R., Goyal, L., Hansen, J., Krishnan, A., Bergesen, J. and Sinha, P. (2017). 'Life cycle assessment of solar photovoltaic microgrid systems in off-grid communities', *Environ. Sci. Techno*l., 51(2), 1043-1052. Available at: https://doi.org/10.1021/acs.est.6b05455	Kenya	Solar-Cadmium Telluride hybrid systems i.e., solar PV-lithium ion battery, solar PV-generator, solar PV-battery-generator / power generation	To perform LCA of three microgrid systems: solar PV-battery, solar PV-diesel, solar PV-hybrid and to determine how the impacts compare to each other	1 kWh of electricity consumed	Production, transport, use, and landfill.	Included	GaBi	GaBi v.6 and Ecoinvent	Primary and secondary data	Not performed	Not specified	GWP, HTP, FEP, POFP, PMFP, AP, TETP	Performed	Performed (type of analysis not specified)
Akinyele, O., Rayudu, K. and Nair, K. C. (2017). 'Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria', *Renew. Energy*, 101, 537-549. Available at: https://doi.org/10.1016/j.renene.2016.09.017	Nigeria	Solar-monocrystalline solar PV/ power generation	To assess the life cycle carbon footprints and energy flows of PV systems.	1 W	Poduction and use	Included	Not specified, equations used	Ecoinvent	Secondary data	Not performed	IEA-PVPS and IPCC	GWP, CEDP , EPBT, NER/EROI	Not performed	Not performed
Wettstein, S., Muir, K., Scharfy, D. & Stucki, M. (2017). 'The environmental mitigation potential of photovoltaic-powered irrigation in the production of South African Maize', *Sustainability*, 9(10). Available at:	South Africa	Solar-multicrystalline solar PV/ power generation	LCA to determine the potential of replacing grid-powered irrigation with solar PV powered irrigation in maize production.	1 kg of maize stored	Use	Included	Not specified, equations used	Ecoinvent 3.3	Primary and secondary data	Not performed	IPCC 2013, Cumulative energy demand, ILCD, Ecological scarcity 2013	GWP, FDP, FEP, MEP, PMFP, AP, LUP, WDP	Not performed	Not performed

https//doi.org/10.3390/su910772														
Serrano-Luján, L., Espinosa, N., Abad, J. and Urbina, A. (2017). 'The greenest decision on photovoltaic system allocation', *Renew. Energy*, 101, 1348-1356. Available at: https://doi.org/10.1016/j.renene.2016.10.020	138 countries including Ethiopia, Mozambique, Zambia, Botswana	Solar- solar PV (thin-film, crystalline silicon, Organic PV)/ power generation	Evaluation of silicon, thin-film, and OPV solar cells to avoid high CO2 emissions by identifying a sustainable geographical manufacturer and installation place.	1 kWp	Production, transport, and use.	Included	Not specified, equations used	Not specified, primary and secondary data used	Secondary data	Not performed	Not specified	GWP, EPBT, EROI	Not performed	Not performed
Okoko, A., Reinhard, J., von Dach, S. W., Zah, R., Kiteme, B., Owuor, S. and Ehrensperger, A. (2017). 'The carbon footprints of alternative value chains for biomass energy for cooking in Kenya and Tanzania', *Sustain. Energy Technol. and Assess.*, 22, 124-133. Avalable at: https://doi.org/10.1016/j.seta.2017.02.017.	Kenya and Tanzania	Bioenergy- firewood, biogas, charcoal, jatropha, briquettes/ solid and liquid biofuel/ thermal	To calculate the carbon footprint of jatropha oil, biogas, firewood, crop residue briquettes and firewood.	I MJ of energy delivered to the pot	Feedstock production, processing, transport, and use	Included	SimaPro	Ecoinvent 3.1	Secondary data	Allocation: type of allocation not specified	IPCC	GWP	Not performed	Not performed
Partey, T., Frith, B., Kwaku, Y. and Sarfo, D. A. (2017). 'Comparative life cycle analysis of producing charcoal from bamboo, teak, and acacia species in Ghana', *Int. J. Life Cycle Assess.*, 22(5), 758-766. Available at: https//doi.org.10.1007/s11367-016-1220-8	Ghana	Bioenergy- charcoal/solid biofuel/ thermal	To quantify and compare the environmental impact of producing charcoal.	1 MJ of energy produced	Feedstock production and processing	Excluded	SimaPro	Ecoinvent 3 and Idemat 2015	Primary and secondary data	Not performed	CML 2001	Eco-cost method: MDP HH, GWP, AP, EP, ecotoxicity	Not performed	Not performed

Somorin, O., Di Lorenzo, G. and Kolios, A. J. (2017). 'Life-cycle assessment of self-generated electricity in Nigeria and Jatropha biodiesel as an alternative power fuel', *Renew. Energy*, 113, 966-979. Available at: [https://doi.org/10.1016/j.renene.2017.06.073.](https://doi.org/10.1016/j.renene.2017.06.073)	Nigeria	Bioenergy-jatropha/ liquid biofuel/ power generation	To quantify environmental impacts of jatropha biodiesel in power generation.	1 kg of fuel consumed in engine per year	Feedstock production, processing, transportation, and use	Included	SimaPro 8.03.14	Agrifood, Ecoinvent	Primary and secondary data	Allocation by energy content	ReCiPe midpoint	GWP, EP, AP, ODP, FDP, MDP, IRP, POFP, PMFP, ecotoxicity, TAP, FEP, MEP	Not performed	Not performed
Amouri, M., Mohellebi, F., Zaïd, A. & Aziza, M. (2017). 'Sustainability assessment of Ricinus communis biodiesel using LCA Approach', *Clean Technol. Environ. Policy*, 19(3), 749-760. Available at: https://doi.org/10.1007/s1009	Algeria	Bioenergy-castor oil/ liquid biofuel/ transport	To analyse greenhouse gas emission, ecosystem quality, human health, and energy return on investment associated with biodiesel production from castor bean oil.	1 tonne of biodiesel production	Feedstock production, processing, and transport	Included	SimaPro 8.1	Ecoinvent 3.1	Primary and secondary data	Allocation by energy content	Impact 2002+	GWP, HH, EP, TAP, LUP, TETP NEV, EROI	Performed	Not performed
Pradhan, A. and Mbohwa, C. (2017). Life cycle assessment of soybean biodiesel production in South Africa: a preliminary assessment, International Renewable and Sustainable Energy Conference (IRSEC). 4th-7th December 2017. Available at :https//doi.org/10.1109/IRSEC.2017.8477393	South Africa	Bioenergy-soybean/ liquid biofuel/ transport	To analyse greenhouse gas emission and energy use in biodiesel production from soybean.	1 GJ of biodiesel (not explicitly defined)	Feedstock production, processing, and transport.	Not specified	Not specified, equations used	Not specified	Secondary data	Allocation by mass	Not specified	GWP, ER	Not performed	Not performed

Lansche, J. and Müller, J. (2017). 'Life cycle assessment (LCA) of biogas versus dung combustion household cooking systems in developing countries: a case study in Ethiopia', *J. Clean Prod*., 165, 828-835.Available at: https://doi.org/10.1016/j.jclepro.2017.07.116.	Ethiopia	Bioenergy-biogas/gaseous biofuel/ thermal	LCA comparing the combustion of dung and biogas in households.	1 MJ of heat delivered to the pot	Feedstock processing, energy production and use.	Included	GaBi	Ecoinvent 2002	Primary and secondary data	Substitution	Not specified	CED, GWP, AP, EP, HTP, TETP	Not performed	Not performed
Ayodele, R., Ogunjuyigbe, O. and Alao, A. (2017). 'Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria', *Appl. Energy*, 201, 200-218. Available at: https://doi.org/10.1016/j.apenergy.2017.05.097	Nigeria	Bioenergy-biogas production from municipal solid waste/gaseous biofuel/ thermal	LCA to assess the environmental impacts and energy potential of electricity generation from waste from 2016 to 2035.	Average annual waste managed between 2016 and 2035	Waste transportation to landfill, landfill gas recovery, and energy production.	Not specified	Not specified, equations used	Not specified	Secondary data	Not performed	IPCC, US Environmental Protection Agency	GWP, AP, EP	Not performed	Not performed
Mahlangu, N. and Thopil, G. A. (2018). 'Life cycle analysis of external costs of a parabolic trough Concentrated Solar Power plant', *J. Clean. Prod*., 195, 32-43. Available at: https://doi.org/10.1016/j.jclepro.2018.05.187	South Africa	Solar-concentrated solar power, BoS/ power generation	To use LCA to determine externalities and the impacts that contribute to the externalities of Concentrating Solar Power. To determine the costs of the environmental impacts throughout the life-cycle stages of the CSP plant.	1 kWh	Production, transport, use, and landfill	Included	GaBi	GaBi and Ecoinvent	Secondary data	Not performed	Cost Assessment of Sustainable Systems, 2008 (end-point weighting)	GWP, HH, LOB, LEC, DM	Performed	Uncertainty identified (uncertainty analysis not done)

Vrech, A., Ferfuia, C., Bessong Ojong, W., Piasentier, E. and Baldini, M. (2018). 'Energy and environmental sustainability of jatropha-biofuels chain from nontoxic accessions in Cameroon', *Environ. Prog. Sustain. Energy*., 38(1), 305-314. Available at: https://doi.org/10.1002/ep.12928	Cameroon	Bioenergy-liquid biofuel from jatropha/ power generation	To quantify emissions and primary energy demand from the production of biodiesel from jatropha in comparison to conventional diesel oil.	1 MJ per MJ of jatropha vegetable oil	Feedstock production, processing, transport, and use. Feedstock production, processing, and transport.	Included	SimaPro	Ecoinvent	Primary and secondary data	Allocation based on energy content	Not specified	GWP, CED, LUP	Not performed	Not performed
Ishimoto, Y., Yabuta, S., Kgokong, S., Motsepe, M., Tominaga, J., Teramoto, S., Konaka, T., Mmopelwa, G., Kawamitsu, Y., Akashi, K. and Ueno, M. (2018). 'Environmental evaluation with greenhouse gas emissions and absorption based on life cycle assessment for a Jatropha cultivation system in frost- and drought-prone regions of Botswana', *Biomass Bioenergy*, 110, 33-40. Available at: https://doi.org/10.1016/j.biombioe.2017.12.026	Botswana	Bioenergy-jatropha/ liquid biofuel / thermal	To assess greenhouse gas emission and absorption from jatropha cultivation in semi-arid regions.	1 kg of jatropha per hactare *(Not explicitly defined)*	Feedstock production, processing, and transport.	Included	Not specified	Ecoinvent v3	Primary and secondary data	Not performed	Not specified	GWP	Not performed	Not performed

Ayodele, R., Ogunjuyigbe, O. and Alao, A. (2018). 'Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria', J. Clean. Prod., 203, 718-735. Available at: https://doi.org/10.1016/j.jclepro.2018.08.282	Nigeria	Bioenergy-biogas production from municipal solid waste/ gaseous biofuel/ thermal	LCA to quantify greenhouse emission reduction potential in municipal solid waste by recovering biogas and analysing the amount of fossil diesel that can be displaced by biogas.	Average annual waste managed between 2017 and 2036	Waste transportation to landfill, landfill gas recovery, and energy production.	Not specified	Not specified, equations used	Not specified	Secondary data	Not performed	Not specified	GWP	Not performed	Not performed
Sundberg, C., Karltun, E., Gitau, J., Kätterer, T., Kimutai, G., Mahmoud, Y., Njenga, M., Nyberg, G., Roing de Nowina, K., Roobroeck, D. and Sieber, P. (2018). ' Biochar from cookstoves reduces greenhouse gas emissions from smallholder farms in Africa', Mitig. Adapt . *Strat. Glob. Change*, 1-15. Available at: https://doi.org/10.1007/s11027-020-09920-7.	Kenya	Bioenergy-biochar/ solid biofuel/thermal	To calculate GHG emissions from using biochar and cookstoves	Net energy for cooking per household for 1 year	Feedstock production, processing, and use.	Not specified	Not specified	Not specified	Primary data	Not performed	Not specified	GWP, PMFP	Not performed	Not performed
Todde, G., Murgia, L., Deligios, A., Hogan, R., Carrelo, I., Moreira, M., Pazzona, A., Ledda, L. and Narvarte, L. (2019). 'Energy and environmental performances of hybrid photovoltaic irrigation systems in Mediterranean intensive and super-intensive olive orchards', *Sci. Total Environ*., 651, 2514-	Morocco and Portugal	Solar-multicrystalline solar PV-grid/ power generation for irrigation	To assess and compare the environmental impact of a high peak-power hybrid PV irrigation system for olive orchards located in Morocco and Portugal.	1kWh of electricity generated and 1kWp of hybrid PV irrigation system installed	Production, transport, use, and recycle.	Included	Not specified	Not specified	Primary and secondary data	Not performed	Not specified	GWP, CEDP, EPBT, CPBT, EROI	Not performed	Not performed

2523. Available at: https://doi.org/10.1016/j.scitotenv.2018.10.175														
Carvalho, R., Lindgren, R., Yadav, P. and Nyberg, G. (2019). Bioenergy strategies to avoid deforestation and household air pollution in western Kenya, 27th European Biomass Conference and Exhibition, Portugal. 27-30 May 2019. Available at: https//doi.org/10.5071/27thEUBCE2019-4BO.15.3	Kenya	Bioenergy-wood fuel/ solid biofuel/ thermal	To analyse the environmental impacts of biomass for cooking.	Not defined	Feedstock production, processing, transport, and use.	Not specified	Simapro 8.5, LEAP	Ecoinvent and Agrifood	Primary and secondary data	Not performed	Not specified	GWP, PMFP, AP, LUP, AD, WDP, MEP, FEP	Not performed	Not performed
Carvalho, R., Yadav, P. and García-López, N, Lindgren, R., Nyberg, G., Diaz-Chavez, R., Upadhyayula, V., Boman, C. and Athanassiadis, D. (2020). 'Environmental sustainability of bioenergy strategies in western Kenya to address household air pollution', *Energies*, 13(3) 719. Available at: https://doi.org/10.3390/en13030719	Kenya	Bioenergy-wood fuel/ solid biofuel/ thermal	To assess the environmental impacts of bioenergy value chain to support decision making.	Not defined	Feedstock production, processing, transport, and use.	Not specified	SimaPro	Not specified	Secondary data	Allocation by mass	ReCiPe	GWP, PMFP, OFP-HH, TAP, WDP, FEP, MEP, MDP, FDP, LUP	Not performed	Not performed
Banacloche, S., Herrera, S. and Lechón, Y. (2020). ' Towards energy transition in Tunisia: sustainability assessment of a hybrid concentrated solar power and biomass plant', *Sci. Total Environ.*, 744.	Tunisia	Solar and bioenergy-concentrated solar power and biomass (CHP) solar collector, gasification boiler, BoS/power	LCA to calculate the environmental and socioeconomic impacts of a hybrid CSP-biomass plant.	1 kWh of electricity generated	Production, transport, and use, landfill.	Included	SimaPro	Not specified	Primary and secondary data	Not performed	Environmental footprint	GWP, ODP, IRP, OFP-HH, PMFP, HTNP,HTCP, TAP, FEP,MEP, TEP, FETP, LUP,WDP, RDP	Not performed	Not performed

Available at: https://doi.org/10.1016/j.scitotenv.2020.140729		and heat generation												
Herrera, I., Rodríguez-Serrano, I., Garrain, D, and Lechón, Y. (2020). ' Sustainability assessment of a novel micro solar thermal: biomass heat and power plant in Morocco', *J. Ind. Ecol*., 1-14. Available at: https://doi.org/10.1111/jiec.13026	Morocco	Solar and bioenergy-solar thermal, biomass (CHP) solar collector, boiler, BoS (e.g., thermal storage)/power and heat generation	LCA to calculate environmental and socioeconomic impacts of a CSP-biomass supply chain, levilised cost of electricity, and abatement costs.	1 kWh of electricity generated	Production, transport, use, and landfill.	Included	Not specified	World Input and Output Database (WIOD), EORA database	Primary and secondary data	Not performed	ILCD	GWP, ODP, IRP, OFP-HH, PMF, HTNP ,HTCP, TAP, FEP,MEP, TEP, FETP, LUP, WDP, RDP	Not performed	Not performed
Patrizi, N., Bruno M., Saladini, F., Parisi, L., Pulselli,R., Bjerre, A. and Bastianoni, S. (2020) 'Sustainability assessment of biorefinery systems based on two food residues in Africa', *Front. Sustain. Food Syst*, 4, 522614. Available at: https://doi.org/10.3389/fsufs.2020.522614	Egypt and Ghana	Biogas-starch feedstock and lignocellulosic (cassava and corn)/solid biofuel/ application not stated	LCA of bioethanol production from cassava and corn food waste.	I ton of biodiesel	Post cultivation processes that generate bio-waste (burden-free because of recycling feedstock), transport to the biorefinery, and production of bioethanol.	Excluded	SimaPro	Ecoinvent 3	Secondary data	Not performed	CML	GWP, AP, EP	Not performed	Not performed

Notes:

BoS- Balance of Systems; CHP- combined heat and power; CSP- Concentrated solar power; PV- photovoltaic; W-watt; kWh- kilowatt hour; MWh- megawatt hour; GWh- gigawatt hour; kWp- kilowatt peak; MJ- megajoule; PV- photovoltaic; LPG- liquefied petroleum gas; ^{b} capital goods for PV and wind comprise power generation and distribution infrastracture i.e. system components; for biogas- digester; biomass- farm machinery at field level, and/or equipment for feedstock processing;AETP- aquatic ecotoxicity potential; ADP- abiotic depletion potential; AP- acidification potential; CC- climate change; CED- Cumulative energy demand; CPBT- CO2 payback time; DEP- dioxins emission potential; DM- damage to materials; EP-eutrophication potential; EPBT- energy payback time; ER- energy ratio; EROI- energy return on investment; FEP- freshwater eutrophication; FDP- fossil depletion; FPBT- financial payback time; GWP- global warming potential; HH- human health; HTP- human toxicity; IRP- ionising radiation potential; LEC- local effects on crops; LOB- loss of biodiversity; LUC- land-use change; LUP- land-use Potential; MEP- marine eutrophication; METP- marine ecotoxicity potential; MDP- metal depletion; NER- net energy ratio; NEV- net energy value; NREV- net renewable energy value; ODP- ozone depletion; OFP-HH- Ozone formation potential human health; PMFP- particulate matter formation potential; POFP- photochemical oxidant formation potential; RDP- resource depletion potential; TAP- terrestrial acidification potential; TETP- terrestrial ecotoxicity potential; WDP- water depletion potential.

Table A 3: Research challenges and gaps of performing life cycle assessment of renewable energy in Africa, the implications of these issues, and recommendations for future research

Research challenge/ gap/issues	**Description**	**Implications**	**Recommendation for future research**	**Reference to the main section**
Type of assessment	Emphasis on environmental issues. Social and economic aspects are not adequately researched.	Mitigating environmental issues can create unintended or intended social and economic consequences.	Need for integrated LCA addressing environmental, issues life cycle cost, and social impacts to understand the feasibility, effectiveness, and consequences of mitigation measures.	3.2.1 Goal definition
Renewable energy source and technology	Lack of studies on geothermal power and a low number of studies on wind and hydropower in Africa despite being the largest sources in installed capacity. Inadequate LCAs on battery technologies for off-grid applications despite the significance of decentralisation on Africa's energy access targets. Few to no LCAs of newer generations of renewable energy technologies e.g., thin-film solar PV and third generation and advanced biofuels. Few LCAs on	Unawareness of the extent of damage particularly for local impacts. Scarce or unavailable data to draw on to implement mitigation strategies in light of the growth of the renewable energy sector. The implications of Africa's energy access targets on climate change, toxicity, and resource depletion potential particularly at the end-of-life are understated. Inadequate data to forecast the environmental impact of newer generations in line with the forecasted growth of Africa's renewable energy sector.	Studies to explore different power generation technologies (i.e., geothermal power, onshore and offshore wind power, hydropower, newer generations of renewable energy), transport (electric vehicles and biofuels), and storage (lead-acid and lithium-ion batteries).	3.1.1, Bioenergy, 3.1.2 Solar, 3.1.3 Other renewable energy: wind and hydropower

	transport: biofuels and electricity.	Inadequate data to inform policies on biofuel blending and electric mobility.		
Goal definition	Lack of proper goal definition.	The intended use of the results and the target audience are unknown. The applicability of the results in decision contexts is limited.	Goal definition should follow ISO guidelines and include the reason for conducting the study, the intended use of the results, the target audience, and the limitations of the chosen methodology.	3.2.1 Goal definition
Functional unit	Functional units are not defined in some studies or interchanged with reference flow, i.e., defined without specifying the function of the system. The effect of different functional units on LCA results of technologies with similar functions is not fully understood (i.e., energy, mass, land area, volume, distance).	Functional units affect decision-making at the micro, meso, and macro-level and determine the effectiveness of mitigation measures. Functional units affect the interpretation of results and effectiveness of mitigation decisions.	Functional units should be clearly defined and carefully selected because they determine why studies are conducted and how LCA results are interpreted. Need to compare the effect of different functional units of the same technology and identify their suitability for various contexts.	3.2.2.1 Functional unit

System boundary	Lack of transparency in system boundary definition. End-of-life omission in studies.	Burden shifting from one life cycle stage to another. The extent of system boundary and the included resource flows may affect the usability of the results in decision contexts. Scarce data on end-of-life pathways to inform mitigation decisions in light of the impending waste challenge in Africa. Particularly, implications on metal depletion, greenhouse gas emission, ecotoxicity, acidification, and eutrophication.	Studies should be explicit about the inclusion or exclusion of processes and their implication on completeness for product modelling. Need for dedicated studies on the end-of-life for all renewable energy technologies to assess Africa's preparedness and readiness to address potential issues of reusing, recycling, landfilling, and incinerating.	3.2.2.2 System boundary
Primary and secondary data	Not all studies state the software and databases used. Use of mathematical equations instead of software to manually compute LCA.	Uncertainties of LCA results affect their accuracy, reliability, and usability. May lead to over-estimation or under-estimation of results hence inaccurate conclusions.	Where commercial software and database are unavailable, studies can use open source software, e.g., Open LCA.	3.2.3.1 Foreground and background data
Representativeness	Time and geographical representativeness. Some studies use outdated data because of the unavailability of up-to-date data while others use databases developed for Europe and North America without adapting them to study contexts, thus, creating uncertainties in the results.	None-representative data does not reflect the actual situation in Africa and may lead to inaccurate conclusions and interventions that are not relevant for the continent.	Time and geographical representativeness should be considered by adapting the database to study contexts.	3.2.3.2.1Time representativeness; 3.2.3.2.2 Geographical representativeness

Life cycle inventory	Lack of transparency in the inventory of some studies, while in some instances the inventories are not shown.	The reproducibility of data is affected.	Studies should include comprehensive inventories, outlining foreground and background data.	3.2.3 Life Cycle Inventory
Completeness in impact assessment	Most studies analyse only climate change potential or selected impact categories and exclude others.	Data should be carefully considered because it creates burden-shifting across impact categories.	Completeness in impact coverage avoids burden shifting from one impact category to another.	3.2.4 Life Cycle Impact Assessment
Impact assessment	Absence of regional or national characterisation factors. Non-climate change impact categories are under researched (e.g., ecotoxicity, human health, land-use, acidification and eutrophication, resource depletion).	The use of global characterisation factors and those created for other regions without adapting them to African conditions gives inaccurate results and conclusions. Insufficient evidence to support mitigation initiatives, perform monitoring and evaluation or establish policy and regulatory instruments to govern the renewable energy sector in Africa.	There is a need for national LCA roadmaps to include regional and national characterisation factors which should be integrated into commercial and open-source LCA software. There is a need for more comprehensive LCA studies in terms of impact coverage across all life cycle stages.	3.2.4.1 Impact assessment method
Normalisation and weighting	Studies use world normalisation and weighting factors because of the absence of regional or national factors.	None-representative normalised and weighted methods may lead to inaccurate LCA results and conclusions.	There is a need for national LCA roadmaps to include regional and national normalisation and weighting factors which should be integrated into commercial and open-source LCA software.	3.2.4.6 Normalisation and weighting
Uncertainty analysis	Most studies do not perform uncertainty analysis.	Uncertainties regarding reliability of the LCA results and their interpretation.	Uncertainty analysis is important to test the robustness of LCA results.	3.2.5 Interpretation

Supporting Information Paper 2: A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value?

Table A 4: Keyword search and search results for business models of renewable energy in Africa

Database	**Search strings**	**Search field**	**Search results**	**Relevance to topic**	
				Included	**Excluded**[a]
Scopus, Google scholar and Web of Science	"business model" AND " renewable energy" AND "Africa"	Title, abstract, keywords	70	39	31
	"specific business model" AND "renewable energy" AND "Africa"	Title, abstract, keywords	19	9	10
	"business model" AND " specific renewable energy source" AND "Africa"	Title, abstract, keywords	41	11	30

Table A 5: Summary of the business models in the reviewed studies

Reference	**Country**	**Technology / application**	**Business model type**	**Business model archetype**	**Value proposition**	**Key partnerships**	**Key resources**	**Key activities**	Channels	**Customer segments**	**Customer relationship**	**Revenue model**	**Cost**
[5] J. Guajardo, Repayment performance for pay-as-you-go solar lamps, Energy Sustain Dev. 63 (2021) 78-85. https://doi.org/10.1016/j.esd.2021.06.001.	Kenya, Malawi, Uganda, and Tanzania	Decentralised solar PV: solar-lamps/ electricity generation.	User-side	Pay-as-you-go (rent-to-own).	Distribution of solar lamps to off-grid customers through pay-as-you-go payment plan to reduce the upfront cost that inhibits adoption or access.	Company partners with manufacturers and distributors globally to disseminate solar lamps.	Solar lamps.	Distribution of solar lamps, remote access and control of solar lamps, troubleshooting, and repossession logistics.	Distribution networks comprising local shops, agents, local entrepreneurs.	Households	Rent-to-own payment plan allows customers to pay in weekly and monthly installments of between 3 to 10 months using mobile money. The money is paid to the distribution network.	Time-based pricing- a given period that a customer is given access to the lamps and pre-pays for its use in regular installments. Unlock price (total amount paid to unlock the systems for unlimited use) is USD $15 with a downpayment of 20%-26% of the unlock price.	Microfinance.
[6] Yang, F. & Yang, M. (2018). Rural electrification in sub-Saharan Africa with innovative energy policy and new financing models. Mitigation and Adaptation Strategy for Global Change, 23, 933-952. https://doi.org/10.1016/j.egypro.2019.01.001	Sub-Saharan Africa (country not specified)	Decentralised solar PV: pico systems, micro-grids/ electricity generation	User-side	(i) Pay-as-you-go (rent-to-own); and (i) Pay-per-service unit.	First-time access to affordable electricity through micro-grids and solar home systems.	Not explicitly defined	Solar home systems and micro-grids	Distribution of solar home systems and electricity generation from mini-grids.	Not explicitly defined	Households	Long-term payment plan for pay-as-you-go systems or continuous engagement for pay-per-service-unit.	Deposit for solar home system is $ 20 followed by installments that accumulate to $ 182.5 The solar home system is replaced after 4 years.	Not explicitly defined

[7] A. Cabanero, L. Nolting, A. Praktiknjo, 2020. Mini-grids for the sustainable electrification of rural areas in Sub-Saharan Africa: assessing the potential of keymaker models, Energies, 13, 6350. https://doi.org/10.3390/en13236350.	Nigeria	Decentralised solar PV: mini-grid/ electricity generation.	User-side	(i) Pay-for-energy-consumed; and (ii) KeyMaker model (productive use).	The mini-grid supplies electricity to farmers. Under the KeyMaker Model, the operator runs agro-processing machinery, processes locally grown produce, and sells them to markets beyond the community.	Local farmers and mini-grid operator.	Mini-grid infrastructure, agro-processing equipment, and financial resources.	Electricity production and supply and processing farm products.	Not explicitly defined.	Local farmers.	Crop supply and electricity purchase agreements between the mini-grid operator and farmers. The agreement is mutually beneficial i.e., the mini-grid operator is the off-taker of farm produce while farmers utilise mini-grid electricity (both parties are suppliers and customers).	Revenue from the sale of electricity i.e., 0.56 USD/kWh.	Capital and operation expenditure for the mini-grid and KeyMaker Model infrastructure (debt, equity, and grants).
[8] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E. Ackom, X. Vallve, S. Szabó, Electrification of sub-Saharan Africa through PV/hybrid mini-grids: reducing the gap between current business models and on-site experience. Renew. Sust. Energ. Rev. 91 (2018) 1148-61. https://doi.org/10.1016/j.rser.2018.04.018.	Sub-Saharan Africa (not specified)	Decentralised solar PV: Hybrid mini-grids/ electricity generation	User-side	Pay-for-energy consumed.	Three types of services offered by solar PV systems domestic use, productive use, and social use.	Not explicitly defined	Solar PV mini-grids	Energy generation and distribution	Not explicitly defined	Households	Not explicitly defined	Not explicitly defined	Levilised cost of electricity from mini-grids.

[9] C. Muchunku, K. Ulsrud, D. Palit, W. Jonker-Klunne, Diffusion of solar PV in East Africa: what can be learned from private sector delivery models? WIREs Energy Environ. 7 (2017) 1-5. https://doi.org/10.1002/wene.282.	East Africa: Kenya, Tanzania, Uganda, and Rwanda	Decentralied solar PV: solar home systems, mini-grids, pico systems/electricity generation	User-side	(i) Retail (outright purchase); (ii) Py-as-you-go; (iii) Consumer financing; (iv) Fee-for-service (rent); and (v) Pay-for-energy consumed.	(i) Retail: a delivery model for basic lighting (ii) Pay-as-you-go: end-user financing facilitated by mobile money. (iii)Consumer financing: a partnership between an energy company and financing institutions. (iii) Mini-grids provide Tier 2 and 3 level access; and (iv) Fee-for-service: stand-alone mini-grids They provide charging and rental services. The business retains ownership of the products and provides maintenance services.	Not explicitly defined.	Solar lanterns	Distribution, installation, maintenance, renting	(i) Multi-level supply chains i.e., supplier, distributor, retailer; (ii) Face-to-face marketing by sales agents (solar lanterns); and (iii) Products are stored in depots and distributed through networks.	Households and businesses	Flexible repayment plan in the pay-as-you-go model e.g., daily, weekly or monthly installments over a long duration.	(i) Revenue from sales; (ii) Fixed installments in the pay-as-you-go model; (iii) Prepaid electricity tariff for mini-grids; and (iv) Fee-for-service for rented products.	(i) Solar lantern- USD 6 to 10; (ii) Mini-grid capital expenditure: USD 6000 to 13000/kWh.

[10] R. Ford. J. Hardy, 2020, Are we seeing clearly? The need for aligned vision and supporting strategies to deliver net-zero electricity systems, Energy Policy,111902. https://doi.org/10.1016/j.enpol.2020.111902.	East, Central, and South Africa, United States, Europe, South America, Asia, and Australasia	Decentralisation, decarbonisation, digitalisation: varied renewable energy sources/ electricity, heat, and transport	User-side	(i)Independent power producers; (ii)Prosumers; (iii) Pay-per-service unit; (iv) Smart meter services; (v) Peer-to-peer pltforms; and (vi) Demand-side management.	Trends: (i) Increased customer engagement in energy production (ii)Electrification of end-use sectors increases micro-generation and storage; (iii) Increased competition in electricity generation improve performance and capacity of batteries; (iv)Community operated grids and peer-to-peer trading are increasing grid defection; (v) Advances in IT applications and demand-side management. Step changes: (i)Electricity generated by multiple producers and stored in a central battery (ii)Increase in captive use with grid electricity	Not explicitly defined	Mixed renewable energy technologies	Energy generation and supply	Not explicitly defined	Residential, commercial, industrial, and the utility grid.	Not explicitly defined	Not explicitly defined	Not explicitly defined

					only used for back-up; (iii) Service models that provide new offerings besides energy e.g., comfort; (iv) Roll out of smart meters will tap customer-side of the meter opportunities; (v) Simplified power purchase agreements that allow independent power producers to sell electricity directly to consumers and not the grid. Innovation (i) Cost-effective storage solutions; (ii) Peer-to-peer trading facilitated by blockchain. (iii) Ethical investments in community energy.								

[11] N. Mukisa, R. Zamora, T. Tjing, Viability of the store-on grid scheme model for grid-tied rooftop solar photovoltaic systems in Sub-Saharan African countries, Renew. Energy, 178 (2021) 845-863. https://doi.org/10.1016/j.renene.2021.06.126.	Kenya, Madagascar, Zimbabwe, Namibia, Rwanda, Cameroon, Niger, Mali, Cote d'Ivore, Bukina Faso, Togo, Senegal, and Eswatini.	Decentralised solar PV: roof-top PV/ electricity generation	User-side	Prosumer (store-on-grid)	Energy and cost savings for Prosumers, profitability to all stakeholder groups, cost-effective approach to financing solar PV projects, reduction in greenhouse gas emissions, saving on land space as rooftop PV are utilised.	Government, prosumers (building owners), and utility companies.	Micro-grid with battery energy storage system. The micro-grid comprises prosumers with roof-top PV that stores surplus electricity in a battery system.	Electricity generation, storage, and supply to the grid, maximise self-consumption by prosumers, operation and maintenance, building and rooftop space.	Marketing and sensitisation of building owners or industries. Governments and civil organisations mainly conduct the sensitisation excercise.	Building owners, industries, and third-party developers.	Long PPA contracts and battery use contracts between the prosumers, governments, and utility companies.	Power purchase agreement price for prosumers i.e., time-of-use rate and average rate (the tariffs per country are given), governments earn revenue from tax levy and battery use-fees, utilities sell electricity fed into the grid and generate revenue.	(i) Prosumer: capital and operation expenditure of the solar PV (ii) Governments: capital and operation expenditure of the batteries (iii) Utility: capital and operation expenditure of the grid. All costs are explicitly defined in the paper.
[12] K. Umoh, M. Lemon, 2020. Drivers for and barriers to the take up of floating offshore wind technology: a comparison of Scotland and South Africa, Energies, 13, 5618. https://doi.org/10.3390/en13215618.	South Africa	Utility-scale wind/ electricity generation.	Utility-side	Infrastructure operation	Attain sustainable development goal 7 targets.	Existing supply chains e.g., onshore wind energy actors e.g., manufacturers, developers, and installers.	Wind turbines, digital platforms for tracking, assembly facility at the Port of Cape Town.	Electricity generation	Not explicitly defined	Utility grid	Not explicitly defined	Corporate power purchase agreement price.	Capital and operation expenditure, levilised cost of electricity. Cost aspects are not extensively defined.

[13] V. Kizilcec, P. Parikh, Solar home systems: a comprehensive literature review for Sub-Saharan Africa, Energy Sustain Dev. 58 (2020) 8-89. https://doi.org/10.1016/j.esd.2020.07.010.	Sub-Saharan Africa (country not specified).	Decentralised solar PV: solar home sytstem/ electricity generation.	User-side	(i) Pay-as-you-go (rent-to-own); (ii) Cash sales (outright purchase); (iii) Credit sales; and (iv) Fee-for-service (renting).	Solar home systems provide low-cost energy to off-grid customers and have a high market growth rate.	Not explicitly defined	Solar home systems	Distribution of solar home systems, operation and maintenance, and training.	Not explicitly defined.	Households and SMEs in off-grid areas.	Service contracts between solar-home-system companies and customers. Most solar home systems are tamper-proof hence it is problematic for technicians not trained to handle them to repair the systems.	Multiple revenue streams depending on the business models e.g., regular installments in the pay-as-you-go model, fee for service delivery, outright purchase price etc.	Not explicitly defined
[14] G. Rasagam, D. Zhu, Delivering on the promise of distributed renewable energy entrepreneurship in Sub-Saharan Africa, Curr Sustainable Renewable Energy Rep. 5 (2018) 230-239. https://doi.org/10.1007/s40518-018-0120-x.	Sub-Saharan Africa (country not specified)	Decentralised renewable energy: solar (PV, CSP, solar thermal), biofuel (incineration, gasification, anaerobic digestion), small-scale wind, small hydropower.	User-side	Pay-as-you-go i.e., (i) Product design; (ii)Consumer financing and after-sale services; (iii) Platform and metering; and (iv)Distribution Other business: (i) Smart metering with mobile money; (ii) Energy efficiency	Small-scale decentralised renewable energy is attractive to entrepreneurs who target price-sensitive markets like remote or rural settings	i)Partnerships between. utilities and entrepreneurs to implement trial business models (ii)Partnerships to enhance connectivity using solar solutions (iii)Partnerships between entrepreneurs and other vertical markets	Solar PV, CSP, solar thermal, biomass briquette bioenergy technologies, small-scale wind, community hydropower plant	Distribution, sales, and retail.	Distribution networks.	Client from residential, industrials, agricultural, communication, and transport sectors.	Customer interface of pay-as-you-go platform, mobile payment platforms and data collection systems (e.g., Mobile money (mpesa) and real-time data collection on energy usage and system performance (BBOXX)).	Not explicitly defined.	Blended finance and private sector investment. Breakdown of costs is not given.

[25]G. Maltitz, A. Gasparatos, C. Fabricius, The rise, fall and potential resilience benefits of jatropha in Southern Africa, Sustainability, 6 (2014) 3615-3643. https://doi.org/10.3390/su6063615.	Southern Africa	Bioenergy: jatropha/ biodiesel production.	User-side	(i) Conract farming: outgrower (ii)Smallholder farming (iii)Plantation farming	Energy crop cultivation models for biofuel production for blending petroleum at the national level, export, and diversifying income. Outgrower schemes are preferred in densely populated areas, unlike plantations.	Not explicitly defined	Jatropha energy crop and land.	Cultivation	Network of buyers for outgrower schemes.	Bioenergy companies	Not explicitly defined	Not explicitly defined	Not explicitly defined
[26] C. Gabriel, J. Kirkwood, Business models for model businesses: lessons from renewable energy entrepreneurs in developing countries, Energy Policy, 95 (2016) 336-49. https://doi.org/10.1016/j.enpol.2016.05.006.	Eleven African countries (e.g., Senegal, South Africa, Somalia, Tanzania, Zambia, Uganda), Asia, and Latin America	Solar, wind, biomass, hydropower, other/ electricity and thermal applications	User-side	(i)Consultancy; (ii) Outright purchase; and (iii) Engineering Procurement and Construction (EPC).	(i)Consultants offer early business stage consultancy services (ii)Distributors: sale of components. (ii)Integrators implement large-scale turnkey energy systems. (i) Inventors: they invent, develop, and distribute their own renewable energy technologies to individual users	Networks, local technicians, manufacturers and suppliers, government, communities, non-governmental organisations, utilities, and local businesses.	Renewable energy technologies, financial resource-es (e.g., investors), human resources (sub-contractig, staff etc).	Project development, networking, installation, maintenance, financing (tenders and grants), and EPC.	(i)Consultants: Word of mouth; (ii)Distributors: direct sales, micro-franchising in remote areas, after-sales services; and (iii)Integrators: direct sales and after-sales services.	Households, small businesses, government, commercial customers.	(i)Consultants: low customer retention because the need for consultancy services ends once the customers install their renewable energy systems, direct contact with customers but not ed-users. (ii)Integrators: indirect relationship with end-users of energy.	(i)Consultancy: project development fees; tenders, (ii)Distributors: tenders, sales; (iii)Integrators: EPC price.	(i)Consultants: low overhead; (ii)Distributors: capital and operating expenditure; (iii)Integrators: high capital and operating expenditure.

[28] M. Barry, A. Creti, 2020. Pay-as-you-go contracts for electricity access: Bridging the "last mile" gap? A case study in Benin, Energy Econ. 90, 104843. https://doi.org/10.1016/j.eneco.2020.104843.	Benin	Decentralised solar PV: pico solar system, solar home systems/ electricity generatio	User-side	Pay-as-you-go (rent-to-own)	Distribution of solar home systems and pico systems on a pay-as-you-go basis.	Telecommunication and solar energy company.	Pico solar systems and solar home systems.	Distribution installation, and training.	Not explicitly defined	Households	Long-term relationship between customer and distributors. The payment plan allows customers to pay for the solar home systems for up to 24 weeks.	€96 per unit paid over 24 week installments.	Not explicitly defined
[29] J. Knuckles, Business models for mini-grid electricity in base of the pyramid markets. Energy Sustain. Dev. 31 (2016) 67-82. https://doi.org/10.1016/j.esd.2015.12.002.	Tanzania, Nigeria, Rwanda, Mali, and Zambia	Mini-grids/ electricity generation	User-side	(i)Community owernership models; (ii) Mini-grid developer ownership; (iii) Operator business model.	(i)Mini-grid developer ownership Electricity use in households is cheaper than kerosene. (ii) Operator model The mini-grid developer constructs and sells the mini-grid to a third party or the community but operates it. This model reduces the operation costs for developers because they do not own the system.	Not explicitly defined	Mini-grid infrastructure	Installation, operation, and maintenance.	Not explicitly defined	Households, small businesses, anchor clients, and utility.	Electricity from mini-grids is cheaper than alternative lighting. Customers get different service levels depending on the price they are willing to pay. User segments are offered cross-subsidies depending on their income.	Customer prepay and post-pay, energy tariffs, power tariffs, cross-subsidy, connection fees.	Not explicitly defined

[32]J. Amankwah-Amoah, Solar energy in sub-Saharan Africa: the challenges and opportunities of technological leapfrogging. Thunderbird Internat. Bus. Rev. 57 (2015) 15-3. https://doi.org/10.1002/tie.21677.	Ghana, Kenya, Nigeria, and South Africa	Solar PV/ electricity generation	Utility-side and user-side	(i) State model; (ii) NGO and aid model; (iii) Emerging market multinational enterprise model; (iii) Avon model- solar sisters; and (iv) Pay-as-you-go (consumer financing).	(i) State model: government-funded or supported projects; (ii)NGO and aid model: aimed at mobilising private sector investment. (iii)Emerging market multinational model offerslow-cost projects; (v) Avon model: solar sisters-empowers women to start social enterprises that sell solar lamps; and (v) Pay-as-you-go: innovative consumer financing to increase uptake of solar home systems.	Not explicitly defined	Solar PV systems and power stations.	Panel manufacturing in South Africa and battery manufacturing in Kenya.	Not explicitly defined	Households and business	Not explicitly defined	Not explicitly defined	Not explicitly defined

[33] M. Pedersen, Deconstructing the concept of renewable energy-based mini-grids for rural electrification in East Africa. WIREs Energy Environ. 5 (2016) 570-87. https://doi.org/10.1002/wene.205	East Africa	Mini-grids/ electricity generation	User-side	(i) Utility ownership; (ii) Hybrid ownership; (iii) Private ownership; (iv)Community ownership.	(i) Utility ownership through private-public partnerships. (ii) Hybrid ownership: more than one entity owns the infrastructure. (iii) Private ownership: (iv)Community ownership: (a) in legal ownership the community owns the infrastructure and outsources operation and maintenance while (b) in symbolic ownership, the investor or developer owns the infrastructure while the community provides operation and maintenance.	Private Public Partnerships- public and private sector co-finance the projects.	Biomass, hydropower, and solar mini-grid infrastructure.	Operation and maintenance.	Not explicitly defined	Households, businesses, institutions, and anchor clients.	Not explicitly defined	Power purchase agreements for hybrid models.	Financing options: donors, subsidies, and private equity.

[34] P. Rolffs, D. Ockwell, R. Byrne, Beyond technology and finance: pay-as-you-go sustainable energy access and theories of social change, Environ. Plan. A. 47 (2015) 2609-2627. http://dx.doi.org/doi:10.1177/0308518X15615368.	Kenya	Decentralised solar PV: solar home system/ electricity generation	User-side	Pay-as-you-go (rent-to-own)	Distribution of solar home systems on pay-as-you-go to provide energy services. Case studies of M-KOPA, Mobisol, and Azuri.	M-KOPA ans Mobisol have partnerships with a telecommunication company.	Solar home systems and financing.	Distribution, maintenance, user training, and feasibility studies.	(i) M-KOPA: dealer networks, helpline, monitoring by technical teams, after-sales services; (ii) Mobisol: marketing agents, after-sales services for 36 months, and helpline; and (iii) Azuri: local dealers.	Households	(i) M-KOPA: payment plan using mobile money. The payment period is 12 months; (ii) Mobisol: payment plan using mobile money and other banking services. The payment period is 36 months; and (iii) Azuri: payment using scratchcards. The payment period is 18 months.	(i) M-KOPA: a deposit of USD 28.50 followed by instalments of USD 165. (ii)Mobisol: deposit of USD 27 to 86 depending on the size of the system followed by instalment of USD 10 to 47. Azuri: variable downpayment amount and subsequent payments.	(i) M-KOPA: grants, impact investors, debt, partner finance; (ii) Mobisol: grants and partner finance; and (iii) Azuri: grants, collaboration with investors, partnered with local vendors and technicians for distribution, installation, and maintenance.
[35] I. Scott, A business model for success: enterprises serving the base of the pyramid with off-grid solar lighting. Renew. Sustain. Energ. Rev. 70 (2017) 50-55. https://doi.org/10.1016/j.rser.2016.11.179.	Africa (country not specified)	Decentralised solar PV: solar home systems / electricity generation	User-side	Business models for subsistence markets (e.g., pay-as-you-go, fee-for-service, pay-per-service unit). Not explicitly defined.	Not explicitly defined	Organisations operating in the subsistence energy market must collaborate to address voids in the market institutions. Partnerships offer financial and technical assistance and address voids in the market and institutions.	Solar lighting products for subsistence markets.	Community participation in social enterprises.	(i)Partnerships in the value network can fill voids in the distribution network and sales. (ii)Capacity building can address issues with marketing or sales services.	Communities in off-grid areas.	Community engagement in product development, training, and business activities such as filling voids in institutions.	Not explicitly defined	Financial support or subsidies are crucial to the success of social enterprises.

[36] I. Da Silva, G. Batte, J. Ondraczek, G. Ronoh, C. Ouma, Diffusion of solar energy technologies in rural Africa: trends in Kenya and the luav experience in Uganda. 1st Africa Photovoltaic Solar Energy Conference and Exhibition, (2014) 106-115. https://doi.org/10.5071/1stAfricaPVSEC2014-3CK.1.2.	Kenya and Uganda	Decentralised solar PV: pico PV/ electricity generation	User-side	(i)Community ownership; and (ii) Pay-as-you-go.	Distribution of Pico PV systems to off-grid users. Community-based organisations (CBOs) are the intermediaries between the company and users. CBOs collect monthly installments for the PV systems on behalf of the company.	SACCO, CBOs, and local governments	Pico PV system	Distribution of pico PV systems and after-sales support.	Not explicitly defined	Households	Community-based organisations conduct sensitisation exercises on a payment plan, savings and revenue collection. After-sales support is given through local technical teams.	Purchase price USD 130. The equipment is available through outright purchase or on a payment plan of between 3 to 12 months.	Capital cost is raised from private investors, SACCO, crowdfunding, and donors.
[37] F. Almeshqab, T. Ustun, Lessons learned from rural electrification initiatives in developing countries: insights for technical, social, financial and public policy aspects, Renew. Sust. Energ. Rev. 102 (2019) 35-53. https://doi.org/10.1016/j.rser.2018.11.035.	Senegal and Kenya	Decentralised solar PV: micro-grid and diesel-powered micro-grid/ electricity generation	User-side	Fee-for-service (renting) (community charging station)	A charging station that provides the community with light battery charging and lighting services.	Not explicitly defined	Solar PV system	Electricity generation and battery charging. Other activities are not explicitly defined.	Not explicitly defined	Households	Households charge batteries at the charging station.	Not explicitly defined	Not explicitly defined

[38]M. Ogeya, C. Muhoza, O. Johnson, Integrating user experiences into mini-grid business model design in rural Tanzania, Energy Sustain. Dev. 62 (2021) 101-112. https://doi.org/10.1016/j.esd.2021.03.011.	Tanzania	Decentralised solar PV: mini-grid/ electricity generation	User-side	(i) Pay-for-energy consumed; and (ii) Consumer financing.	(i) Generation of electricity from hybrid mini-grid that is coupled with a diesel generator. The mini-grid powers small loads in households and businesses. (ii) Credit to finance appliances. The developer offers bronze, silver, Tanzanite, and gold packages for different appliances and quantities.	Developer and the public sector: co-finance. The developer finances the generation infrastructure while the public sector the distribution network.	Mini-grid with backup diesel generator and distribution network.	Electricity generation and distribution.	(i) Sales agents to help customers purchase electricity units. (ii) Technical assistants that offer customer support.	Households, businesses, and institutions.	The customers pay in installments of 6 months for silver, tanzanite, and gold packages.	(i) Silver package: USD 26 upfront and USD 5 monthly installments for 6 months. (ii) Tanzanite package: USD 36 upfront and USD 8 monthly installments for 6 months. (iii) Gold package: USD 59 upfront and USD 13 monthly installments for 6 months. (iv) Pre-paid fixed tariff of TZsh 4/kWh.	Not explicitly defined
[39] G. Benschc, M. Grimma, M. Huppertzb, J. Langbeinc, J. Petersd, Are promotion programs needed to establish off-grid solar energy markets? Evidence from rural Burkina Faso, Renew. Sustain. Energy. Rev. 90 (2018) 1060 -1068. https://doi.org/10.1016/j.rser.2017.11.003.	Bukina Faso	Decentralised solar PV: solar home system/ electricity generation	User-side	Fee-for-service (rent)	Distribution of branded solar home systems on a fee-for-service basis. Sale of unbranded solar home systems.	Not explicitly defined	Solar home systems	Maintenance for fee-for-service systems.	Sales shops	Households	After-sales services for branded products.	Renting fees and cash sales.	Not explicitly defined

[40] J. Sloughter, J. Isakson, Y. Mak, A. Schleicher, H. Louie, K. Shields, M. Salmon, Designing a sustainable business plan for an off-grid energy kiosk in Chalokwa, Zambia. 2016 IEEE Global Humanitarian Technology Conference (GHTC), (2016) 401-405. https://doi.org/10.1109/GHTC.2016.7857312.	Zambia	Decentralised solar PV and portable battery kits/ electricity generation	User-side	(i) Fee-for-service: community energy kiosk; and (ii) Pay-as-you-go (rent-to-own portable battery kits).	Renting portable battery kits to households over a two-year period. Users are given lighting appliances on credit.	Non-governmental organisation	Energy kiosk and portable lead-acid battery kts.	Energy generation, battery renting, and charging.	Not explicitly defined	Households	Payment plan for portable battery kits.	USD 2 upfront payment followed by USD 4 monthly installments over 11 months.	Consumer financing for appliances and batteries.
[41] J. Barrie, H. Cruickshank, Shedding light on the last mile: a study on the diffusion of pay as you go solar home systems in Central East Africa, Energy Policy, 107 (2017) 425-436. http://dx.doi.org/10.1016/j.enpol.2017.05.016.	Central East Africa	Decentralised solar PV: solar home system/ electricity generation	User-side	Pay-as-you-go (rent-to-own)	The pay-as-you-go model incentivises customers to adopt solar home systems by allowing customers to use the systems and pay for them in installments.	Sales agents and solar technicians.	Solar home systems	Distribution of solar home systems, operation and maintenance, and training.	Group promotion events and one-on-one customer interaction with sales agents.	Households.	Long-term relationship between customer and distributors. The payment plan allows customers to pay for the solar home systems for up to 105 weeks.	Time-based pricing within the repayment term. Customers pay a down payment of USD $ 10 followed by weekly installments of USD $1.25.	Microfinance.
[42] I. Bisaga, N. Puźniak-Holford, A. Grealish, C. Baker-Brian, Scalable off-grid energy services enabled by IoT: a case study of BBOXX SMART Solar. Energy Policy, 109 (2017) 199-207. https://doi.org/10.1016/j.enpol.2017.07.004.	Kenya and Rwanda	Decentralied solar PV: solar home systems/ electricity generation	User-side	(i) Pay-as-you-go; and (ii) Consumer financing.	Distribution of solar home systems through an innovative financing plan. The systems' performance, fault diagnosis, payment status are remotely monitored by SMART Solar.	Not explicitly defined	Solar home systems	Sale of solar home systems, maintenance, financing, and asset-backed securities.	Call centre to facilitate communication with users.	Households	Network of technicians to offer maintenance services. Users pay for the solar home systems over a 36-month duration.	Pay-as-you-go payment plan of £4 per month.	Debt from investors is used to finance the production of the solar home systems i.e., solar panels, batteries, and charge controllers.

[43] E. Bacchetti, C. Vezzoli, P. Landoni, Sustainable product-service system (S.PSS) applied to distributed renewable energy (DRE) in low and middle-income contexts: a case studies analysis. Procedia CIRP, 47 (2016) 442-447. https://doi.org/10.1016/j.procir.2016.03.085.	Tanzania and Kenya	Decentralised solar PV: micro-grid, solar home systems, pico systems/ electricity generation	User-side	(i) Leasing; (ii) Renting (energy charging station); (iii) Product oriented- pay-as-you go (rent-to-own); (iv)Pay-for-energy consumed.	(i) Product service systems satisfy users' needs and shift perceived value from ownership to access. The main focus is access, stakeholder configuration, and user satisfaction; (ii) The leasing model offers users solar home systems and appliances for a set duration; (iii) The renting model offers charging and renting services; (iv) The product-oriented model sells solar home systems and offers maintenance services; (v) The pay-for-energy-consumed model supplies power.	Not explicitly defined	Solar PV micro-grid, balance of systems, and solar home systems.	Energy generation, energy supply, leasing solar home systems, renting batteries and solar lamps, and maintenance.	Not explicitly defined	Households and small businesses	Users buy, lease, and rent portable batteries and solar lamps.	(i) Lease-daily fees paid over the lease duration; (ii) Rent-membership fee and pay-per-use; (iii) Pay-as-you-go-selling price and maintenance fee; (iv)Operator model-connection fees and pay-per-use.	Not explicitly defined

[44] S. Emili, F. Ceschin, D. Harrison, Product–service system applied to distributed renewable energy: a classification system, 15 archetypal models and a strategic design tool. Energy Sustain Dev. 32 (2016) 71-98. https://doi.org/10.1016/j.esd.2016.03.004.	Botswana and South Africa	Decentralised solar PV: stand-alone systems and mini-grids- isolated and connected/electricity generation	User-side	(i) Product-oriented: pay-to-purchase with service delivery; (ii) Use oriented: pay-to-lease and pay-to-rent; (iii) Results-oriented: pay-per-unit consumed and pay-per-energy consumed.	(i) Selling PV systems with service delivery and training; (ii) Consultancy for isolated and grid-connected community-owned mini-grids; (iii) Leasing energy systems and energy-using products; (iv) Renting energy systems and energy-using products; (v) Access to energy and energy-using products through pay-per-use; (vi) Access to energy and energy-using products through pay-per-unit of satisfaction; and (vii) Battery recharging services.	Not explicitly defined	Pico PV systems, solar home systems, charging stations, isolated mini-grids, grid connected mini-grids.	Distribution, installation, renting, leasing, energy generation and supply, and maintenance.	Not explicitly defined	Households and businesses	Relationships are fostered based on the the terms of the PSS business models.	(i) Pay-per unit satisfaction; (ii) Pay-per-energy consumed; (iii) Pay-to-rent; (iv) Pay-to-lease; (v) Pay-to-purchase with service delivery.	Not explicitly defined

[45] V. Acker, S. Szablya, H. Louie, A. Pirbhai, Survey of energy use and costs in rural Kenya for community microgrid business model development, IEEE 2014 Global Humanitarian Technology Conference, 2014, 166-173. https://doi.org/10.1109/GHTC.2014.6970277.	Kenya	Decentralised solar PV and wind micro-grid/ electricity generation	User-side	Fee-for-service (renting portable battery kits charged at energy kiosk) (community charging stations)	Community micro-grid (charging station). Households lease portable battery kits that are charged at the energy kiosk.	Not explicitly defined	Solar PV (1.9 kW; lifespan 10 years), small wind turbines (1 kW; lifespan 6 years), large stationary lead-acid battery (400 Ah/ 6 V; lifespan 10 years), portable battery kits (12 Ah/12 V; lifespan 2 years), balance of systems (lifespan 10 years).	Energy generation (no distribution), charging portable battery kits, operation and maintenance of the micro-grid and portable battery kits.	Not explicitly defined.	Households	Household rent and charge portable battery kits (12 Ah 12 V) at the energy kiosk. The batteries can last between 2-3 days before recharging is required.	Enrollment fee (USD $5.8) and monthly subscription fees (USD $ 12.8) per user. Most revenue comes from battery rental fees, mobile phone charging fees (USD $0.23) per phone, revenue from the sale of electrical appliances that are accessories of the battery kits e.g., LED lights, adapters, and cables.	Capital expenditure: wind turbine (USD $ 3722), solar PV (USD $ 2997), 70 portable battery kits (USD $10 075), stationary batteries (USD $ 396), balance of systems (USD $ 3969), and replacement costs. Operation expenditure: salaries, and maintenance.

[46] B. Sovacool, Expanding renewable energy access with pro-poor public private partnerships in the developing world. Energy Strategy Rev. 1 (2013) 181-192. https://doi.org/10.1016/j.esr.2012.11.003.	Zambia and other locations outside Africa	Decentralied solar PV: Solar home system/ electricity generation	User-side	Fee-for-service (renting).	A partnership of several organisations and communities aimed at mitigating the business risk of implementing renewable energy projects in off-grid markets that serve customers who have a low purchasing power. For example, a fee-for-service model for energy service companies (ESCO) that rents 50 Wp solar panels, batteries, sockets, and lights to users. The ESCO retains ownership of the solar panels and provides maintenance services and component replacement.	Public sector, private companies, multilateral development banks, microfinance institutions, and non-profit organisations (5 P).	Solar panels and batteries	Renting, maintenance, component replacement, and training.	Awareness campaigns	Households	(i) Users pay a daily or weekly fees for using the solar panels; and (ii) Technicians conduct regular checks and training to ensure the systems are used efficiently.	The service fee is USD 7 per month per customers.	Debt

[47] C. Friebe, P. Flotow, D. Täube, Exploring the link between products and services in low-income markets: evidence from solar home systems, Energy Policy, 52 (2013) 760-769. http://dx.doi.org/10.1016/j.enpol.2012.10.038.	Sub-Saharan Africa (country not specified)	Decentralised solar PV: solar home system/ electricity generation	User-side	(i) Fee-for-service (renting); (ii) Pay-as-you-go (rent-to-own); (ii)Sales model: cash and credit; and (ii) Consumer financing.	(i) Sales model (a) Cash- users pay for solar home systems and assume ownership. (b) Credit- the company selling the solar home systems offers loans to customers to finance the purchase of solar home systems. Customers pay a downpayment followed by regular installments. (iii) Service model (a) fee-for-service- users pay a fee for the use of solar home systems or for the units of electricity consumed. The ownership of the system remains with the companies. (b) Pay-as-yo-go (rent-to-own) approach.	Partnership between microfonance institutions and companies selling solar home systems.	Customer financing, solar home systems, technical expertise, and advisory services.	(i)Distribution of solar home systems and installation is done by energy companies; (ii) Cash- the user is responsible for maintenance; (iii) Credit- the consumer and energy company are responsible for maintenance; (iv) Fee-for-service- The energy company is responsible for maintenance and take back; (v) Leasing- the energy company is responsible for the maintenance during the payment period. Afterward, the user or company maintains the systems.	Not explicitly defined	Households	(i) Customer and company relationship is fostered because of the payment plan or the ownership model; (ii) Cash- users become owners of the systems once payment is made; (iii) Credit- users become owners following contractual agreements; (iv) Fee-for-service- the company retains ownership. The user pays for use of the system; and (v)Leasing- ownership is transferred from companies to users upon completion of payment.	(i) Cash- the user pays in full for the solar home systems; (ii) Credit- the user and microfinance institutions pay regular installments to cover the credit for the solar home systems; and (iii)Fee-for-service- the user pays a predetermined amount for the services offered or a tariff for the electricity consumed.	(i) Leasing- the company meets the upfront cost of the solar home systems; and (ii) Fee-for-service- company finances the solar home systems

[48] A. Ellegård, A. Arvidson, M. NordstrÖm, O. Kalumiana, C. Mwanza, Rural people pay for solar: Experiences from the Zambia PV-ESCO project. Renew. Energy, 29 (2004) 1251-1263. Available at: https://doi.org/10.1016/j.renene.2003.11.019.	Zambia	Decentralised solar PV: solar home system/ electricity generation	User-side	Fee-for-service (renting)	Solar home systems are rented and installed on users' property.	The supply chain	Solar home systems	Distribution, installation, and maintenance.	Not explicitly defined	Households and businesses	Not explicitly defined	Fee-for-service (USD 7)	Not explicitly defined
[49] J. Lukuyu, R. Fetter, P. Krishnapriya, N. Williams, J. Taneja, 2021. Taneja, Building the supply of demand: Experiments in mini-grid demand stimulation. Dev. Eng. 6, 100058. https://doi.org/10.1016/j.deveng.2020.100058.	Kenya and Tanzania	Decentralised solar PV: mini-grid/ electricity generation	User-side	(i) Pay-for-energy consumed; and (ii) Appliance financing (productive use).	Clean affordable electricity. Tariff subsidies and credit to finance the purchase of appliances by mini-grid customers to stimulate the demand for electricity.	Not explicitly defined.	Solar PV mini-grid infrastructure, electric appliances, financing appliances.	Electricity generation and supply, financing electricity appliances.	Not explicitly defined	Households and micro-enterprises in off-grid areas.	Credit plan to procure electric appliances and pay in installments and reduced tariff to incentivise consumption of power.	Revenue from the sale of appliances to customers. Time-of-use and pre-paid fixed tariff.	Capital and operation expenditure of mini-grid infrastructure, procurement of electric appliances to be sold in credit to customers.
[50] G. Kyriakarakos, G. Papadakis, 2019. Multispecies swarm electrification for rural areas of the developing world, Appl. Sci. 9, 3992. https://doi.org/10.3390/app9193992.	Sub-Saharan Africa (country not specified)	Decentralised solar PV: solar home systems, micro-grid/ electricity generation.	User-side	Servitisation (multispecies swarm electrification)	Multispecies swarm electrification' pathway that uses solar home systems independently or as interconnected systems to create DC or AC microgrids aimed at generating more electricity to power large loads.	Not explicitly defined	Flexibility of use either as solar home systems or micro-grids.	Electricity generation and distribution.	Not explicitly defined	Households	Pay-as-you-go. Not explicitly defined.	Not explicitly defined.	Not explicitly defined.

[51] M. Huber, N. Namockel, R. Rezgui, M. Küppers, H. Heger, Electrification seeds: a flexible approach for decentralized electricity supply in developing countries, Energy Sustain Dev.62 (2021) 176-185. https://doi.org/10.1016/j.esd.2021.04.001.	Nigeria	Decentralised solar PV: hybrid-mini-grid (PV-diesel)/ electricity generation	User-side	Prosumer-(electrification seed)	Prosumers generate electricity from hybrid mini-grids for captive use and retail to small and medium-sized enterprises and households. Customers avoid the high upfront cost of purchasing diesel generators for self-generation.	Not explicitly defined	Solar PV mini-grid infrastructure-lifetime 15 years.	Electricity generation and retail.	Not explicitly defined	Households and businesses	Productive uses of electricity to increase average consumption per user.	Pre-paid and post-paid fixed-tariff for seed-supply (0.3 €/kWh) which is 7% cheaper than generating electricity from diesel generators (self-supply).	Capital and operation expenditure of the solar PV system. LCOE reduces by 4.7% by switching from self-generation to seed-supply (i.e., electrification seed). Net present value (NPV) of €430 and internal rate of return (IRR) of 18.2%.
[52] S. Sewchurran, I. Davidson, 'Why Solar PV is such a lucrative option for South African municipal customers', 2021 Southern African Universities Power Engineering Conference/ Robotics and Mechatronics/Pattern Recognition Association of South Africa. (2021) 1-7. https://doi.org/10.1109/SAUPEC/RobMech/PRASA52254.2021.9377024.	South Africa	Decentralised solar PV: rooftop/electricity generation	User-side	Prosumer	Self-generation, consumption, and exporting power to the grid to lower users' energy bills and earn revenue. Industrial and commercial clients have large roof spaces that are ideal for solar panel installation.	Not explicitly defined	Rooftop PV	Energy generation and exporting to the grid.	Not explicitly defined	Utility grid	Power purchase agreement between prosumers and the grid.	Feed-in-tariff: USD 0.045.	Nt explicitly defined

[53] S. Venkatachary, J. Prasad, R. Samikannu, Challenges, opportunities, and profitability of virtual power plant business models in sub-Saharan Africa- Botswana. International Journal of Energy Economics and Policy, (2017) 2146-4553. https://www.econjournals.com/index.php/ijeep/article/view/4973.	Botswana	Decentralised renewable energy: smart grids in virtual power plants (prosumers, aggregators, demand response)/ solar PV, wind/ electricity generation	User-side	Prosumer	Prosumers trade in wholesale through virtual power plants.	Not explicitly defined	Solar PV systems and smart grid infrastructure.	Integration of solar energy systems.	Not explicitly defined	Wholesale market	Not explicitly defined	Not explicitly defined	Not explicitly defined
[54] S. Mandelli., C. Brivio, M. Leonardi, E. Colombo, M. Molinas, E. Park, M. Merlo, The role of electrical energy storage in Sub-Saharan Africa. J. Energy Storage, 8 (2016) 287-299. https://doi.org/10.1016/j.est.2015.11.006.	Tanzania	Decentralised energy storge/ electricity generation	User-side	Energy storage models	Electrical energy storage for hydropower and PV micro-grid.	Private-public partnership in co-financing capital and operation expenditure.	Electrochemical batteries	Energy storage	Not explicitly defined	Institution	Not explicitly defined	Not explicitly defined	Not explicitly defined
[55] A. Troost, J. Musango, A. Brent, Strategic investment to increase access to finance among mini-grid ESCOs: perspectives from Sub-Saharan Africa, 2nd International Conference on Green Energy and Applications, (2018) 29-37. https://doi.org/10.1109/ICGEA.2018.8356268.	East and Southern Africa	Decentralised solar PV: mini-grid)/ electricity generation	User-side	Pay-for-energy consumed	Not explicitly defined	Investors	Mini-grid and financial resources	Financing	Not explicitly defined	Not explicitly defined	Not explicitly defined	Not explicitly defined	Financing options for mini-grids

[56] B. Batidzirai, P. Trotter, A. Brophy, S. Stritzke, A. Moyo, P. Twesigye, A. Puranasamriddhi, A. Madhlopa, 2021. Towards people-private-public partnerships: An integrated community engagement model for capturing energy access needs. Energy Res. Soc. Sci, 74, 101975. https://doi.org/10.1016/j.erss.2021.101975.	Uganda and Zambia	Decentralised solar PV: solar home systems, and mini-grids/ electricity generation	User-side	(i) Pay-as-you-go; and (ii) Pay-for-energy-consumed.	Not explicitly defined	People-Public-Private Partnerships	Solar home systems and solar mini-grids.	Energy generation and sale of solar home systems.	Not explicitly defined	Households and businesses	Not explicitly defined	Not explicitly defined	Not explicitly defined
[57] P. Alstone, D. Gershenson, D. Kammen, Decentralized energy systems for clean electricity access, Nat.Clim. Change, 5, (2015) 305-14. https://doi.org/10.1038/nclimate2512.	Kenya	Decentralised PV: pico systems, solar home systems, mini and micro grids/ electricity generation.	User-side	(i) Pay-as-you-go; and (ii) Pay-for-energy consumed	Environmental, social, economic, and technological benefits of energy access electrification projects.	Not explicitly defined	Solar PV systems	Electricity generation.	Not explicitly defined	Households	Not explicitly defined	Not explicitly defined	Not explicitly defined
[58] M. Njogu, P. Kimathi, I. DaSilva, Community-developer business model promoting social energy enterprises: case study of Mutunguru 7.8MW community-driven small hydropower project, IEEE Africon, (2017) 1143-8. https://doi.org/10.1109/AFRCON.2017.8095643.	Kenya	Hydropower/ electricity generation	User-side	Community ownership (build-own-operate-transfer)	Community-owned mini-grid operated by a private operator. A special purpose vehicle (SPV) was created to operate the mini-grid. A joint venture between equity investor venture and SPV to increase generation capacity. The	Project developers, a public company limited by shares, the community (owner). The Mutunguru hydroelectric company owns ordinary shares (100%) while the equity investor owns preferential shares (100%).	Hydropower mini-grid	Engineering, procurement, training, construction, operation and maintenance.	Not explicitly defined	Utility (anchor client)	Not explicitly defined	Feed-in-tariff. The revenue is shared in the community.	Grants debt, and equity investment.

					investor builds, owns, operates, and transfers ownership of the infrastructure to the community after 10 and 25 years of operation.								
[59] T. Buchholz, I. Da Silva, J. Furtad, Power from wood gasifiers in Uganda: a 250Kw and 10 Kw case study. Proceedings of the Institution of Civil Engineers- Energy, 165 (2012) 181-196. https://doi.org/10.1680/ener.12.00005.	Uganda	Solid biofuel: wood biomass / electricity generation	User-side	Outgrower schemes: vertically integrated business model for sourcing feedstock.	For a 150 kW gasifier: firewood is used as feedstock to power the gasifiers. The fuelwood is sourced from a 90ha plantation. Electricity is generated for captive use.	Fuelwood supply chain	250 kW and 10 kW gasifier	Procuring feedstock, electricity production, and maintenance.	Fuelwood logistics chain	Industrial (self-consumption)	Not explicitly defined	Not explicitly defined	Fuelwood cost is US$0.03/kWh, the capital cost is US$2087/kW, the electricity production cost is US$0.29/kWh.
[60] R. Hamid, R. Blanchard, An assessment of biogas as a domestic energy source in rural Kenya: developing a sustainable business model. Renew. Energy, 121 (2018) 368-376. https://doi.org/10.1016/j.renene.2018.01.032.	Kenya	Biogas micro-grid/thermal applications	User-side	Pay-for-energy consumed.	Affordable clean energy that is cheaper than alternative traditional fuel. Biogas retail price is € 0.55/kg compared to €1.65 for LPG, €0.65 kerosene, €0.17 charcoal, and €0.08 firewood.	Not explicitly defined	Digesters: fixed dome floating drum inflatable tubular flow, flexi biogas, crop residue, water, cattle manure, and land.	Construction of digesters, biogas generation and use.	Not explicitly defined	Households	Not explicitly defined	Revenue from the sale of biogas i.e € 0.67 per day per household. The revenue is for consumption of 4 kWh per day per household.	Daily operating expenditure is €19.85, net present value €2764, internal rate of return 56%, discounted payback period is 20 months, biogas breakeven price €0.442.

[61] P. Jagger, I. Das, Implementation and scale-up of a biomass pellet and improved cookstove enterprise in Rwanda. Energy Sustain. Dev. 46 (2018) 32-41. [https://doi.org/10.1016/j.esd.2018.06.005.](https://doi.org/10.1016/j.esd.2018.06.005)	Rwanda	Solid biofuel: biomass pellets and microgasification cook stoves/ thermal application	User-side	(i) Outright purchse; (ii) Fee-for-service (rent).	Biomass pellets purchase contracts and renting of microgasification cookstove. The cookstoves are leased because most households cannot afford the purchase price. The pellets are cost-competitive with charcoal. Customers have access to cleaner energy at a cost below or at par with the baseline energy cost. the feedstock is sourced from rural customers and government-owned eucalyptus plants.	Government and local farmers	Feedstock is sourced from tree branches, elephant grass, eucalyptus plants, and sawdust. Biomass pellets, microgasification cookstoves.	Distribution of cookstoves and pellets, repairs, training, and replacement of cookstoves.	Marketing and after-sales repairs.	Households	After-sales repairs	The pallet power purchase price is inclusive of the leasing fee. Three payment packages: basic (30 kg pellets per month and 1 stove targeted for small households), preferred (45 kg pellets per month and 2 stoves targeted for medium households), and deluxe (60 kg pellets per month and 3 stoves targeted for wealthy households). The deluxe package was phased out because of low demand.	Capital expenditure of USD 60 per stove.

[62] S. Bryant, H. Romijn, Not quite the end for Jatropha? Assessing the financial viability of biodiesel production from Jatropha in Tanzania, Energy Sustain Dev. 23 (2014) 212-219. http://dx.doi.org/10.1016/j.esd.2014.09.006.	Tanzania	Bioenergy: jatropha/ biodiesel production.	User-side	(i)Smallholder outgrower; (ii) Independent producer of biodiesel.	Smallholder jatropha models managed by farmers who grow the crops on the boundary land around their farms to generate additional income. The model discourages farmers from substituting their food crop production with jatropha.	Not explicitly defined	Jatropha seeds (feedstock), land, and feedstock processing plant.	Sourcing seeds from farmers, (extraction of pure vegetable oil from jatropha seeds, degumming, transesterification and neutralisation , dry washing, high-quality biodiesel, Seedcakes, waste products from the production of pure vegetable oil, are converted into briquettes for sale to replace firewood use.	Farmers take their yield to collection centers. Thereafter, the seeds are transported to the processing plant by renting trucks that deliver products upcountry and would otherwise make the return trip empty. Renting trucks on return journey cuts transportation costs associated with sourcing seeds from decentralised systems.	50,000 smallholder farmers	Farmers are not required to have long hedges of jatropha that are more than a few 100m. The average annual sale for each farmer is 10kg dullhead seeds. The average jatropha yield per meter hedge is 0.1 to 0.8 kg- the yield is affected by rainfall patterns, soil fertility, pests, the density of the jatropha shrubs, etc).	Revenue from the sale of pure vegetable oil.	Cost of purchasing jatropha seeds from farmers. Capital and operation expenditure of producing biodiesel from jatropha seeds.

[63] G. Maltitz, K. Setzkorn, A typology of Southern African biofuel feedstock production projects. Biomass and Bioenergy, 59 (2019) 33-49. https://doi.org/10.1016/j.biombioe.2012.11.024	South Africa, Zambia, Tanzania, Mozambique, Madagascar, and Malawi	Bioenergy/ electricity generation	User-side	(i) Contract farming (outgrowers); (ii) Plantations; (iii) Hybrid; and (iv) Smallholder farming.	Energy crop cultivation models for biofuel production to meet local energy needs, blend petroleum at the national level, export, and diversify income.	Private-public partnerships e.g., NGOs, local governments, and bilateral organisations.	Energy crops e.g., jatropha, sugarcane, croton, palm oil, coconut oil, sunflower, canola, soybean, maize, and land.	Cultivation	Not explicitly defined	Corporates, local utilities, bioenergy processors and millers.	Not explicitly defined	Not explicitly defined	Not explicitly defined
[64] N. Hultman, E. Sulle, C. Ramig, S. Sykora-Bodie, Biofuels investments in Tanzania: policy options for sustainable business models. J. Environ. Dev. 3 (2012) 331-361. https://doi.org/10.1177/1070496511435665.	Tanzania	Liquid biofuel/ application not specified	User-side	Farming models (i) Small-scale farming; (ii) Large-scale plantation; (iii) Contract farming: outgrower models; (iv) Hybrid models; (v) Purchase contracts; (vi) Land leases; (vii) Share cropping; (vii) Joint ventures: community provides land and has shares in the business model. Milling models	(i) Plantation model: centralised bioenergy crop production and processing. It is mostly used for crops with high capita requirements e.g., sugarcane. Constraints in land acquisition or lease in Tanzania hinder uptake of this model Land is communally owned and transferring ownership may take up to 2 years. (ii) Contract farming:	Private public partnerships between farmers, corporates, investors the government, etc.	Biofuel feedstock and land	Bioenergy crop production, milling, refining, and distribution, end-use.	(i)Transport contractors; (ii)Existing distribution networks e.g., retail outlets; (iii)Intermediary traders.	Bioenergy companies buy feedstock from farmers and sall the final products to end-users.	Not explicitly defined	Not explicitly defined	Not explicitly defined

				(i)Cooperative mills (ii) Share-ownership (iii) Supply contracts with distributors refineries; (iv) Supply contracts at small-scale with local end-users. Refining models High capital cost is a barrier for this business model hence limited options. Distribution models (i) Transport contractors; (ii) Existing distribution networks e.g., retail outlets; (iii)Intemediary traders. End-use models (i)Multifuction platforms (subsidised) (ii) Improved appliances (subsidised) (iii) Use of unrefined oil	outgrower contracts for feedstock delivery to a centralised processing plant. This model is successful in Tanzania due to improving the participation of locals if there is low flexibility when the contracts are for monoculture, farmers are not involved in setting feedstock prices, and lack of legal frameworks to protect farmers and corporates. (iii) Hybrid model: a combination of large and small-scale farming models whereby both corporates and farmers own land and resources. It is best suited for private-public-partnerships .								

[65] L. German, G. Schoneveld, D. Gumbo, The local social and environmental impacts of smallholder-based biofuel investments in Zambia. Ecol. Soc. 16 (2011) 1-17. http://dx.doi.org/10.5751/ES-04280-160412.	Zambia	Liquid biofuel from jatropha/ application not specified	User-side	Contract farming: outgrower schemes	(i) Bioenergy company contracts many small-scale farmers to cultivate jatropha under outgrower contracts. Bioenergy companies are shifting to jatropha-purchase agreements to pay only for the amount of feedstock they buy and minimise side selling. Bioenergy company offers farmers loans in form of seeds, agrochemical to farmers, extension services, licensing, logistics, and storage.	Small-scale farmers	Jatropha seeds (feedstock), land, and labour.	Jatropha cultivation and feedstock sale.	Not explicitly defined	Bioenergy company buys feedstock from farmers.	30-year outgrower contracts between farmers and bioenergy companies. The price of feedstock is determined by the bioenergy company at the time of sale/purchase.	Bioenergy company recovers its investment from the proceeds from the purchase of feedstock from farmers.	Bioenergy company pays a one-off payment of USD 60 followed by USD 15 monthly until harvest. 5% of the profits allocated to the local community.

[67] D. Campbell, M. Danilovic, F. Halila, M. Hoveskog, The clash of business models in emerging economies: the case of wind energy industry in Africa, IJMSIT, 10 (2013) 10-51. [https://www.econstor.eu/handle/10419/97882.](https://www.econstor.eu/handle/10419/97882)	Southern Africa and East Africa	Wind/ electricity generation	Utility-side	(i)Engineering Procurement and Construction; (ii)Independent power producers.	(i) Siemens: manufactures wind turbines, provides services throughout the lifecycle of wind farms, owns projects or delivers them as turnkey solutions, provides finance; (ii) Suzlon: offer products and services throughout the life cycle of wind farms. The company is vertically integrated and delivers all projects as turnkey solutions; (iii)Goldwind manufactures and sales wind turbines, provides services throughout the lifecycle of wind farms, offers debt and equity	Governments and utility companies	Wind turbines	Feasibility studies, manufacturing, operation and maintenance, training the local workforce. Products are sourced locally and internationally.	Manage logistic supply chain to lower transport costs.	Independent power producers, governments, and utility companies.	Delivery of high-quality goods and services to create strong relationships with customer segments.	Sale of wind turbines, service delivery, feed-in-tariff earnings from injecting electricity in the grid.	(i) Siemens: higher costs; (ii) Suzlon: vertical integration results in lower costs; (iii)Goldwind: lower cost.

[68] W. Budzianowski, I. Nantongo, C. Bamutura, M. Rwema, M. Lyambai, C. Abimana, … S. Sow, Business models and innovativeness of potential renewable energy projects in Africa. Renew. Energy, 123 (2018) 162-90. [https://doi.org/10.1016/j.renene.2018.02.039.](https://doi.org/10.1016/j.renene.2018.02.039)	Nine countries (e.g., Kenya, Rwanda, Zambia)	Solar, biofuel, wind, hydropower/electricity generation and thermal applications	Utility-side and user-side	(i) Operator business model; and (ii) Private-public partnerships in financing projects.	Multiple value propositions for renewable energy generation and use.	Suppliers and private-public partnerships to co-finance projects.	Combined heat and power plant, stand-alone solar systems, micro-grids, and concentrated solar power.	Procurement of capital goods from international suppliers, local manufacturing of some components, installation, energy generation, and distribution.	Not explicitly defined	Households, businesses, and utility	Not explicitly defined	Sale of energy, fertilisers from bioenergy plants, and byproducts of gasification. Net metering, pre-paid meters, power purchase agreements, subscription fees, pay-per-unit consumption.	(i) Grid-connected solar investment cost of USD 3500/kW; (ii) Bagasse boiler has a capital cost of about USD 2500/kW compared to USD 1250/kW of combusting biomass in coal-powered plants; (iii) Investment costs of onshore wind projects are USD 2000/kW; and (iv)Hydropower investment cost is about USD 2000-4000/kW.

[69] A. Mahama, 2012 international year for sustainable energy for all: African frontrunnership in rural electrification, Energy Policy, 48 (2012)76-82. [https://doi.org/10.1016/j.enpol.2012.04.046.](https://doi.org/10.1016/j.enpol.2012.04.046)	Ghana	Decentralised Solar PV: solar lantern and energy-efficient cook stoves/ electricity generation	User-side	(i) Outright purchse; (ii)Community owned model.	Solar lantern: The Affordable Lighting for All (ALFA) is a multistakeholder collaboration to implement solar lanterns and energy-efficient cookstoves through commercially viable distribution models. The program issues microfinance to customers. Mini-grid Donor-funded community-owned mini-grid that is operated by a private operator.	Non-governmental organisations, private solar energy companies, and manufacturers, development organisations (donors).	Solar lanterns, energy-efficient cookstoves, mini-grid, battery storage, and microfinance.	Marketing, distribution, and maintenance.	(i)Distribution to end-users; (ii)Marketing and after-sales repairs.	Households and institutions	After-sales repairs	Connection fees, uniform tariff due to subsidies, purchase price of solar lanterns, and cookstoves.	Donor funded projects

[79] C. Jumbe, M. Mkondiwa, Comparative analysis of biofuels policy development in Sub-Saharan Africa: the place of private and public sectors. Renew. Energy, 50 (2013) 614-20. https://doi.org/10.1016/j.renene.2012.07.023.	Fifteen countries in Africa (e.g., Ghana, Angola, and Benin)	Biofuel/ electricity generation, transport	User-side	Farming models (i) Contract farming: outgrower schemes (ii) Land leasing; (iii) Joint ventures (iv)Share cropping; (v)Management contracts; Milling model (i)Cooperative mills (ii) Supply and distribution contracts with large refineries. Distribution models (i) Transport contractors; (ii) Existing distribution networks e.g., retail outlets; (iii)Intermediary traders. End-use models (i)Multifuction platforms (subsidised) (ii) Improved appliances (subsidised) (iii) Use of unrefined oil	(i) The private sector applies its expertise in biofuel development i.e. financing, creation of joint ventures, outgrower schemes, refining, etc. (ii) The public sector stimulates private sector involvement by providing and enabling environment, developing markets and public infrastructure, regulating the sector, providing subsidies, providing institutional arrangements for feedstock acquisition e.g., joint ventures and outgrower schemes. It also promotes rural employment through milling operations.	Private-Public Partnerships	Bioenergy feedstock	Farming, milling, distribution, end-use.	(i)Transport contractors (ii)Existing distribution networks e.g., retail outlets; (iii)Intermediary traders.	Not explicitly defined	Not explicitly defined	Not explicitly defined	Not explicitly defined

[80] Z. Ma, M. Lundgaard, B. Jørgensen, B. (2016). Triple-layer smart grid business model: a comparison between Sub-Saharan Africa and Denmark. IEEE Innovative Smart Grid Technologies,(2016) 347-352. https://doi.org/10.1109/ISGT-Asia.2016.7796410.	Sub-Saharan Africa and Denmark	Smart grids (micro-grids)/ electricity generatio	User-side	Demand-side management	Smart-grids for demand-side management from micro-grid generation. Micro-grids can be clustered and managed by smart-grids to overcome the high installation and distribution costs of large-scale systems.	Not explicitly defined	Micro-grids	Electricity generation	Not explicitly defined	Households, businesses, and publicly-owned buildings.	Not explicitly defined	Dynamic pricing	Not explicitly defined
[81] W. Pailman, W. Kruger, G. Prasad, Mobile payment innovation for sustainable energy access. International Conference on the Domestic Use of Energy (DUE), (2015) 39-44. https://doi.org/10.1109/DUE.2015.7102961.	South Africa, Kenya, Tanzania and Zimbabwe	Decentralised solar PV: solar home systems, pico systems/electricity generation	User-side	(i) Pay-as-you-go (rent-to-own); (ii) Fee-for-service (rent)	(i) Pay-as-you-go: the solar energy company offers credit to users to reduce the upfront cost of purchasing solar home systems followed by monthly installments. (ii) Fee-for-service: the energy company rents solar home systems to users. Users pay the installation fee followed by a power purchase agreement.	Telecommunication companies	Solar home systems and smart meters.	Distribution, installation, monitoring and maintenance.	Not explicitly defined	Households	Pay-as-you-go payment plan	(i) Pay-as-you-go price (mobile money) (ii) Power purchase agreement price	Not explicitly defined

[82] E. Vanadzina, A. Pinomaa, S. Honkapuro, G. Mendes, An innovative business model for rural sub-Saharan Africa electrification. Energy Procedia, 159 (2019) 364-369. https://doi.org/10.1016/j.egypro.2019.01.001.	Sub-Saharan Africa (country not specified	Decentralised solar PV: mini-grid, energy kiosk, energy centre/ electricity generation	User-side	Pay-for-energy consumed.	(i) Energy kiosk and mini-grid: serves a larger community (ii) Energy centre: found in sparsely populated areas. They generate energy and supply it to a base station.	Not explicitly defined	Solar PV system with storage batteries.	Not explicitly defined	Not explicitly defined	Households and small businesses	Not explicitly defined	Electricity tariff, fee-for-service, and connection fees.	Captital and operating expenditure.
[83] Zerriffi, H. (2011). Innovative business models for the scale-up of energy access efforts for the poorest. Current Opinion in Environmental Sustainability, 3: 272-278. Available at: https://doi.org/10.1016/j.cosust.2011.05.002	Multiple locations (e.g., South Africa, Kenya, Malawi).	Decentralised solar PV: mini-grid, solar home systems, pico systems/ electricity and thermal application	User-side.	Financing models: producer-side and consumer-side solutions.	(i) Producer-side: finance along the value chain e.g., venture capital, credit facilities, and cross-subsidies, NGO financing for social enterprises; (ii)Consumer-side: direct finance, leasing and rental models, service models, and third party financing; and (iii) Carbon finance: carbon credits.	Not explicitly defined	Not explicit-ly defined	Not explicitly defined	Not explicitly defined	Not explicitly defined	Not explicitly defined	Not explicitly defined	Financing models: producer-side and consumer models.

[84] I. Bisaga, P. Parikh, Y. Mulugetta, Y. Hailu, 2019, The potential of performance targets (imihigo) as drivers of energy planning and extending access to off-grid energy in rural Rwanda, WIRES Energy Environ, 8, e310. https://doi.org/10.1002/wene.310.	Rwanda	Decentralised solar PV: solar home systems/ electricity generation.	User-side	Performance contracts	A vertical and bottom-up approach to strengthen societal and institutional performance of energy contracts. Households choose energy access targets they wish to imple.	President, ministries, and local governments.	Solar home systems	Household access to solar home systems.	Not explicitly defined.	Households	Not explicitly defined.	Not explicitly defined.	Not explicitly defined.
[85] G. Adwek, S. Boxiong, P. Ndolo, Z. Siagi, C. Chepsaigutt, C. Kemunto, M. Arowo, J. Shimmon, P. Simiyu, A. Yabo, The solar energy access in Kenya: a review focusing on Pay-As-You-Go solar home system, Environ. Dev. Sustain. 22 (2020) 3897-3938. https://doi.org/10.1007/s10668-019-00372-x	Kenya	Decentralised solar PV: solar home systems/ electricity generation	User-side	Pay-as-you-go (rent-to-own)	Distribution of solar home systems on a pay-as-you-go basis. Social (affordability and security of electricity supply), economic (employment creation) benefits.	Telecommunication, solar energy companies, and financial institutions.	Solar home systems	Distribution, installation, monitoring and maintenance.	Sales agents, dealer network, kiosk owners, and word of mouth.	Households	Long-term relationship between customer and distributors. The payment plan allows customers to pay for the solar home systems over a period of time. Customer training, service hubs, and helplines.	(i))M-kopa: Unit price: $ 165, deposit $30, Daily minimum of $ 0.5 per day. Payment is made through mobile money, (i) Azuri technologies: installation $ 10, deposit $ 30-100 depending on size, monthly minimum $ 10-50, maximum payment period is 36 months. Payment is made through scratch cards.	Grants and loans

Supporting Information Paper 3: Environmental evaluation of business models for solar energy: The EBuM framework

Table A6: Description of the components of a solar home system

Source: Solar enegy compny in Kenya

PV module	
Panel capacity	100 Wp
Area of one panel	0.776 m^2
Type of PV	Polycrystalline
Efficiency of one module	16%
Lifetime of solar panels	20 years (baseline scenario); 25 years (business model innovation scenario)
Number of panels exchanged throughout lifetime	0
Weight of one panel	7.45 kg
Country of purchase solar panels	China
PV system generation (sun hours)	8 hours/day
Panel degradation	0.7% per year
Average daily irradiance (Kenya)	5kWh/m^2
Performance ratio	0.75
Balance of system	
Battery	Lead-acid, 1.2 kW
Battery capacity	12V, 100 Ah
Battery country of purchase	China
Lifetime of battery	10 years (replaced once in the baseline scenario); (replaced twice in the business model innovation scenario)
Weight of battery	35 kg
Inflows and outflows	
Water consumption for washing panels	2.5 litres every two weeks
Detergent use for washing panels	Soap is not used
Transport (calculated using Google Maps (road) and ports.com (water))	
Transportation of components from manufacturer to Chinese port by road	Road (lorry of 16 to 32 metric tons)
Transportation of solar panels from China to Kenya by sea	Ship (freight transoceanic ship).
	Distance: 12223.2 km
Transportation of components from Kenyan port to a warehouse in Nairobi or customer	Road (lorry of 16 to 32 metric tons)
	Distance: 816 km

Transportation of components from customer to waste treatment facility	Baseline scenario: road (passenger car), distance 5km, an open dumpsite
	Business model innovation scenario: road (lorry of 16 to 32 metric tons); distance 50 km, recycling facility

Table A7: Description of the components of a ground-mounted 20 kWp solar mini-grid system

Source: Solar energy company in Kenya

a) PV modules	
PV installed capacity	20 kWp
Panel capacity	265W
Number of panels in an array	78
Area of installed capacity	8m^2/ kWp
Area of one panel	1.62 m^2
Type of PV	Multicrystalline
Efficiency of one module	16%
Lifetime of solar panels	25 years (baseline scenario); 40 years (business model innovation scenario)
Number of panels exchanged throughout lifetime	0
Weight of one panel	18 kg
Country of purchase solar panels	China
PV system generation (sun hours)	8 hours/day
Average annual energy yield	27672.84 kWh
Degradation	0.7% per year
Average daily irradiance (Kenya)	5 kWh/m^2
Performance ratio	0.75
b) **Balance of systems**	
Solar/ PV inverter	20 kW (1 pc)
Battery inverter	13.8 kW (1 pc)
Weight of solar inverter	71 kg
Weight of battery inverter	63 kg
Lifetime of inverter	15 years (replaced once in baseline scenario; replaced twice in business model innovation scenario)
Efficiency of inverters	95%
Area of the mounting structure	8m^2/ kWp
Weight of mounting structure	26kg/panel or 16kg/m2
Lifetime of the mounting structure	25 years
Battery	Lead Acid 144kWh;
Battery capacity	48V/3000Ah
Battery lifetime	10 years (replaced twice in baseline scenario; replaced four times in business model innovation scenario)
Number and weight of batteries in the system	Set of 24 pieces, 6000kg in total every 10 years

Country of purchase: inverter, mounting structure, battery,	China
c) **Inflows and outflows**	
Water consumption for washing panels	14.3 litres per day
Detergent use for washing panels	Soap is not used
d) Transport (calculated using Google Maps (road) and ports.com (water))	
Transportation of components from manufacturer to port in China	Road (lorry Euro 3, 16 to 32 metric tons)
	Distance is assumed to be 150 km
Transportation of components from China to Kenya	Ship (freight transoceanic ship)
	Distance: 12223.2 km
Transportation of components from Kenyan port to installation site	Road: (lorry of 16 to 32 metric tons)
	Distance: 816 km
Transportation of components from site to waste treatment facility	Baseline scenario: road (lorry of 16 to 32 metric tons), distance 50 km, recycling facility

Table A8: Description of the components of a roof-mounted 600 kWp commercial-scale PV system

Source solar energy company in Kenya

a) PV modules	
PV installed capacity	600 kWp
Panel capacity	250W
Number of panels in an array	2400
Area of installed capacity	3360m^2
Area of one panel	1.4 m^2
Type of PV	Multicrystalline
Efficiency of one module	15%
Lifetime of solar panels	25 years (baseline scenario); 40 years (business model innovation scenario)
Number of panels exchanged throughout lifetime	0
Weight of one panel	18 kg
Country of purchase solar panels	China
PV system generation (sun hours)	8 hours/day
Average annual energy yield	717 MWh
Degradation	0.7% per year
Average daily irradiance (Kenya)	5 kWh/m^2
Performance ratio	0.75
b) **Balance of systems**	
Solar/ PV inverter	17 kW (10 pcs)
Weight of solar inverter	71 kg
Lifetime of inverter	15 years (replaced once in baseline scenario; replaced twice in business model innovation scenario)
Efficiency of inverters	98%
Area of the mounting structure	109.5m^2
Weight of mounting structure	26kg/panel or 16kg/m2
Lifetime of the mounting structure	40 years

Country of purchase: inverter, mounting structure, battery	China
c) **Inflows and outflows**	
Water consumption for washing panels	342.9 litres per day
Detergent use for washing panels	Soap is not used
d) Transport (calculated using Google Maps (road) and ports.com (water))	
Transportation of components from manufacturer to port in China	Road (lorry Euro 3, 16 to 32 metric tons)
	Distance is assumed to be 150 km
Transportation of components from China to Kenya	Ship (freight transoceanic ship)
	Distance: 12223.2 km
Transportation of components from Kenyan port to installation site	Road: (lorry of 16 to 32 metric tons)
	Distance: 816 km
Transportation of components from site to waste treatment facility	Baseline scenario: road (lorry of 16 to 32 metric tons), distance 50 km, recycling facility

Table A9: Description of the components of a roof-mounted 180 kWp industrial-scale PV system

Source: Solar energy company in Kenya

a) PV modules	
PV installed capacity	180 kWp
Panel capacity	370W
Number of panels in an array	490
Area of installed capacity	1000m^2
Area of one panel	2 m^2
Type of PV	Multicrystalline
Efficiency of one module	15%
Lifetime of solar panels	25 years
Number of panels exchanged throughout lifetime	0
Weight of one panel	18 kg
Country of purchase solar panels	China
PV system generation (sun hours)	6 hours/day
Average annual energy yield	221 MWh
Degradation	0.7% per year
Average daily irradiance (Kenya)	5 kWh/m^2
Performance ratio	0.75
b) **Balance of systems**	
Solar/ PV inverter (replaced once)	50 kW (3 pcs); 25 kW (1 pc)
Weight of solar inverter	84 kg per 50 kW inverter; 61 kg per 25 kW inverter
Lifetime of inverter	15 years (replaced once in baseline scenario; replaced twice in business model innovation scenario)
Efficiency of inverters	96%
Area of the mounting structure	32.85 m^2
Weight of the mounting structure	26kg/panel or 16kg/m2
Lifetime of the mounting structure	40 years
Country of purchase: inverter, mounting structure, battery,	China

c) **Inflows and outflows**	
Water consumption for washing panels	588 litres per day
Detergent use for washing panels	Soap is not used
d) Transport (calculated using Google Maps (road) and ports.com (water))	
Transportation of components from manufacturer to port in China	Road (lorry Euro 3, 16 to 32 metric tons)
	Distance is assumed to be 150 km
Transportation of components from China to Kenya	Ship (freight transoceanic ship)
	Distance: 12223.2 km
Transportation of components from Kenyan port to installation site	Road: (lorry of 16 to 32 metric tons)
	Distance: 816 km
Transportation of components from customer to waste treatment facility	Baseline scenario: road (lorry of 16 to 32 metric tons), distance 50 km, FRELP recycling facility

Table A 10: Inventory for 1kg of lead-acid battery, scale for 1 kg (Spanos et al., 2015)

Material	**Wt %**	**kg**
Lead	69	0.69
Oxygen	2	0.02
Calcium (0.058% of alloyed lead)	0.03	0.0003
Aluminium	0.01	0.0001
Tin	0.4	0.004
Silver (0.02% alloyed lead)	0.01	0.0001
Barium sulfate	0.12	0.0012
Carbon black	0.04	0.0004
Sodium lignosulfonate	0.05	0.0005
Fibre glass mat separator	2.5	0.025
Copper terminals	0.5	0.005
H_2SO_4	6.3	0.063
Water	10.8	0.108
Polypropylene (casing)	7.5	0.075
Integrated circuit	0.0002	0.000002
Printed wiring board	0.04	0.0004
ABS plastic casing	0.76	0.0076

Table A11: End-of-life waste management

a) Solar panels (FRELP: Full Recovery End-of-life PV (Latunussa et al., 2016)

Recycled materials (including losses)	**Dataset**
Scrap aluminium (wrought)	Assumption: 99% of aluminium is recovered ; Melting aluminium scrap post consumer prepared for recycling. 1% loss during remelting; Aluminium, wrought alloy {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | Cut-off, U
Scrap copper	Assumption: 69% of copper is recovered based on literature values.; Copper {RoW}| treatment of scrap by electrolytic refining | Cut-off, U
Silicon	Assumption 96% silicon is recovered; Silicon, multi-Si, casted {RoW}| production | Cut-off, U
Scrap glass	Assumption: 99% glass is recovered; Glass cullet, sorted {RoW}| treatment of waste glass from unsorted public collection, sorting | Cut-off, U
Waste to landfill/ incineration	
Polyethylene terephthalate (incineration)	Assumption 100% of Polyethylene terephthalate is incinerated with electricity recovery; Waste polyethylene terephtalate {RoW}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U; Ecoinvent version 3.5
polyvinylfluoride (incineration)	Assumption 100% incinerated; Waste polyvinylfluoride {RoW}| treatment of, municipal incineration | Cut-off, U
Other Waste plastic mx (Ethylvinylacetate, Glass fibre reinforced plastic) (incineration)	Assumption 100% plastic mixis is incinerated; Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, municipal incineration | Cut-off, UEcoinvent version 3.5
Contaminated flat glass	Assumption: 1% of glass is disposed in sanitary landfill; Waste glass {GLO}| treatment of waste glass, sanitary landfill | Cut-off, U
Contaminated solar glass	Assumption: 1% of glass is disposed in sanitary landfill; Waste glass {GLO}| treatment of waste glass, sanitary landfill | Cut-off, U
Aluminium (sludge containing metallic residue))	Assumption: 1% aluminium is disposed in sanitary landfill; Assumption: 1% aluminium is disposed in sanitary landfill; Waste aluminium {RoW}| treatment of, sanitary landfill | Cut-off, U
Copper (sludge containing metallic residue))	Assumption: 31% copper is disposed in inert landfill; Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill
Silicon (sludge containing metallic residue)	Assumption: 4% of silicon is is disposed in residual material landfill; Waste, from silicon wafer production, inorganic {RoW}| treatment of, residual material landfill | Cut-off, U
Nickel (sludge containing metallic residue))	Assumption100% nickel is disposed in residual material landfill; Nickel smelter slag {RoW}| treatment of, residual material landfill | Cut-off, UEcoinvent version 3.5

b) Lead acid battery (Sullivan and Gaines, 2012)

Recycle recovered materials (10% loss during the recycling process)	**Datasets**
Remelting lead	Assumption 70% lead is recycled; Remelting scrap lead from lead acid battery. 10% loss during remelting process; Lead {RoW}| treatment of scrap acid battery, remelting; Ecoinvent version 3.5

Copper scrap	Assumption 100% copper terminals are recovered and taken to recycling facility; Copper {RoW}| treatment of scrap by electrolytic refining | Cut-off, U
Waste to landfill/ incineration	
Polypropylene (landfill)	Assumption: 100% is incinerated; Waste polypropylene {RoW}| treatment of waste polypropylene, municipal incineration | Cut-off, U
Waste plastic mix (including)Acrylonitrile-butadiene-styrene production (landfill)	Assumption: 100% ABS is disposed in sanitary landfill; Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | Cut-off, U
Copper	Assumption 10% copper is disposed in inert landfill; Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill
Lead oxide alloy	Assumption: 40% landfilling in residual material landfill; Lead smelter slag {GLO}| treatment of, residual material landfill | Cut-off, U
Grid alloy	Assumption 100% landfilled in sanitary landfill; Waste aluminium {RoW}| treatment of, sanitary landfill | Cut-off, U

c) Mounting structure (Broadbent, 2016; Marie and Quiasrawi (2012))

Recycled materials (10% losses during recycling process)	**Dataset**
Aluminium scrap	Assumption 85% aluminium is recovered and recycled; Assumption: 10% of the aluminium is lostduring remelting; Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing
Scrap steel	Assumption 85% steel is recovered and recycled.Assumption: 10% of the steel is lost during recycling; Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Cut-off, U
Concrete gravel	Assumption 20% concrete is recycled; Waste concrete gravel {RoW}| treatment of waste concrete gravel, recycling | Cut-off, U
landfilled/ incineration	
Concrete	Assumption Waste reinforced concrete {RoW}| treatment of waste reinforced concrete, sorting plant | Cut-off, U
Aluminium scrap	Assumption 15% waste aluminium{RoW} sanitary landfill
Steel scrap	Assumption 15% Scrap steel {RoW} inert material landfill

d) Cables (Li et al., 2017)

Recycling	**Dataset**
Copper	90% copper is recycled; Assumption 10% copper is lost during recycling; Copper {RoW}| treatment of scrap by electrolytic refining | Cut-off, U
Steel	99% steel is recycled. Assumption 10% is lost during recycling process;
Waste to landfill/ incineration	
Scrap copper	Assumption 20% of copper is disposed in inert material landfill; Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill
Steel	Asumption 1% Scrap steel {RoW} inert material landfill
Waste polyvinyl chloride (incineration)	Assumption 100% wastepolyvinylchloride is incinerated; Waste polyvinylfluoride {RoW}| treatment of, municipal incineration | Cut-off, U
Waste polyethylene (incineration)	Assumption: 100% incinerated; Waste polyethylene terephtalate {RoW}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U;

e) Inverter (assumption: same recycling rates as solar PV)

Recycled materials (10% recycling losses)	**Datasets**
Aluminium	99% aluminium is recycled; Assumption 10% aluminiumislost during melting; Aluminium, cast alloy {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner | Cut-off, U
Copper	69% copperis recycled; Assumption 10% copper is lost during recycling; Copper {RoW}| treatment of scrap by electrolytic refining
Rolling steel	99% steel is recycled; Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Cut-off, U
Landfill/ incineration	
Polystyrene	Assumption 100% incineration; Waste polystyrene {RoW}| treatment of waste polystyrene, municipal incineration | Cut-off, U
Polyethylene	Assumption 100% incinerated; Waste polyethylene terephtalate {RoW}| treatment of waste polyethylene terephthalate, municipal incineration | Cut-off, U;
polyvinylchloride	Assumption 100% incinerated; Waste polyvinylchloride {RoW}| treatment of, municipal incineration | Cut-off, U
Aluminium	Assumption 11% landfilled; Waste aluminium {RoW}| treatment of, sanitary landfill | Cut-off, U
Copper	Assumption 41% landfilled; residual material landfill
Scrap steel	Assumption 11% landfilled; Scrap steel {RoW}| treatment of, inert material landfill | Cut-off, U
Other waste	The remaining waste inert landfill; Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill
Printed wiring board	Assumption 10% inert landfill; Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill

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