GLOBAL STUDIES INSTITUTE DE L'UNIVERSITÉ DE GENÈVE
COLLECTION « MÉMOIRES ÉLECTRONIQUES »
Vol. 129-2024

Techno-economic and environmental analysis of energy communities in Sub-Saharan Africa. The case of the Democratic Republic of the Congo

Mémoire présenté pour l'obtention
du Master en études africaines par
Ange Nkonko Kibelo Martin's

Rédigé sous la direction de Selin Yilmaz
Jury : Salvatore Di Falco et Yousra Sidqi
Genève, décembre 2023

Abstract

Energy access is significantly constrained in Sub-Saharan Africa (SSA). Various factors simultaneously concur to this phenomenon. However, community-scale renewable energy and energy communities can support an increase in energy access. The literature presents substantial gaps concerning the electricity demand and related generation costs in SSA, specifically in the Democratic Republic of the Congo (DRC), where no literature could be found. Due to its fast-growing demography, addressing data scarcity in DRC is central to achieving universal electricity access. This research investigates the potential techno-economic and environmental impacts of micro-grids in rural solar energy communities. To do so, we develop a dataset providing data on demand estimations that consider the population, appliance ownership in these communities as well as electricity consumption of these appliances, according to which we sized the micro-grid and the storage. A techno-economic analysis is performed to quantify the costs related to the implementation of the system by conducting a levelized cost of energy analysis. Eventually, the CO_2 reduction potential is tested by comparing CO_2 emissions from a diesel generator to CO_2 emissions from PV and batteries. The results show that a 163-kW solar system with a storage capacity of 65 kWh could satisfy the residential load of the modeled community at an LCOE of 0.18 $/kWh. Based on these findings, policy recommendations were proposed to reduce this LCOE. CO_2 reduction potential was estimated to be 3649 tCO_2eq for the whole community. We stress the potential benefits that could result from implementing the energy communities and community-scale energy planning into policies.

Summary

List of Tables

List of Figures

Table of abbreviations

AC	Air Cooling
ANSER	Agence pour l'électrification rurale et péri-urbaine de la RDC
ATP	Ability to Pay
CAPEX	Capital Expenditure
CE	Community Energy
CoC	Cost of Capital
DRC	The Democratic Republic of the Congo
EC	Energy Community
GW	Global Warming
KW	Kilowatt
KWh	Kilo-Watt hour
LCOE	Levelized Cost of Electricity
MG	Mini grid
MICS	Multiple Indicator Cluster Surveys
MTF	Multi-tier Framework
NTL	Non-technical losses
OPEX	Operational Expenditure
PV	(Solar) Photovoltaics
RE	Renewable Energy
SDG	Sustainable Development Goals
SSA	Sub-Saharan Africa
TEA	Techno-economic assessment
TES	Total Electricity Supply
TFC	Total Final Consumption
WM METHOD	Worst Month method
WTP	Willingness to Pay

Acknowledgements

I express my gratitude to my friends and family for their unwavering support. Additionally, I extend my thanks to the PhD students and researchers who engaged in insightful discussions with me on the subject. A particular acknowledgment goes to Arven Sylla, whose relevant insights into techno-economic aspects were invaluable, and I greatly appreciated his support and motivation. My deepest gratitude is reserved for Dr. Selin Yilmaz, whose presence was instrumental in the development of this work. Dr. Yilmaz shared a wealth of knowledge and provided significant assistance throughout the completion of this project. Collaborating with her was a truly enriching experience.

1. Introduction

1. Climate change

The work of the IPCC showed to which extent it is central to limit global warming (GW) to the threshold of 1.5 degrees above pre-industrial levels. GW can be defined as "an increase in combined surface air and sea surface temperatures averaged over the globe and over a 30-year period." (IPCC, 2018). Climate change can be defined as: "A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer"(IPCC, 2012), we are not on a sustainable pathway and, if things remain the same, we will not be able to contain GW to 1.5°, and therefore limit climate change.

This increase in temperature is caused by anthropic activities. It is fundamental to underline that climate change is already affecting the weather of many countries across the globe. Extreme events such as heatwaves (Reuters, 2022), tropical cyclones, droughts, and heavy precipitations are evidence of this. (IPCC, 2023). However, countries are affected unevenly by climate change. According to the IPCC, the countries that contributed the least to climate change are those that are the most vulnerable to it. The IPCC provides a list of observed impacts and losses related to climate change. Countries in Africa are observing the adverse impact on their agriculture and crop production, and the physical availability of water will probably reduce due to droughts. Infectious diseases are becoming more frequent (Marani et al., 2023), same for heatwaves (Perkins-Kirkpatrick & Lewis, 2020) and floods (UN, 2022a), especially in coastal areas. All of these factors translate into displacements and important damages in key industrial sectors. Stressing the importance of climate change mitigation is extremely important as all of this is happening now.

If the threshold is exceeded these effects would intensify in the first place. Impacts will vary in time and space. But for most regions, an increase of 1.5° above the pre-industrial level or 2° above it would result in severe augmentation in the "occurrence and/or intensity of some extreme events" (IPCC, 2023), which would inevitably increase poverty in the African continent, reduce food availability, enhance the chances of extremely hot temperature and affect economic growth. (IPCC, 2023). Important precipitations are likely to become more frequent in central Africa. To avoid overcoming this threshold countries put in place the *Paris Agreement* (PA). Its purpose is to prevent States from emitting too much CO_2. The *Paris Agreement* is characterized by two innovations: stressing out intensively the 1.5/2° threshold, and the implementation of Nationally Determined Contributions (NDCs).

The NDCs are legally binding features of the adoption and mitigation of greenhouse gasses (GHGs). More concretely, the NDCs consist of the expected CO_2 emissions declined on different dimensions, notably CO_2 emissions and CO_2 emissions per unit of GDP. (UNFCCC, 2021). This framework is provided with instances that have the role of evaluating the impact of established NDCs (Salman et al. 2022). Most countries try to attain NDCs through national policies, but some countries are not clear on how they will attain the declared NDCs. Another major limit of NDCs is political discontinuity. A country could declare an NDC but if the government changes this latter could also change its mind. Similar to what happened in the US in 2017 when after his election Donald Trump declared the intention of withdrawing the US from the *Paris Agreement*. The purpose of the *Paris Agreement* is to ensure that emissions reach their peak before 2025 and emissions reduce by 43% at least, before 2030. The PA also highlights the necessity of solidarity from richer nations towards the less wealthy ones.

The PA is not the only framework created to help reach a sustainable pathway; the first tool of this genre was *Agenda 21,* a thorough plan of action to create a world partnership for sustainable development to better the lives of people and safeguard the environment (SDGs, UN). Following *Agenda 21* there was the Millennium Development Goals (MDGs). These 8 goals had the objective of reducing extreme poverty by 2015. To push further these development efforts, in 2015, along with PA, the Sustainable Development Goal (SDG) framework was put in place. The temporal scope is always 15 years (similar to MDGs) but they are defined more precisely. There are 17 and each SDG is declined under various points allowing a much more precise level of definition and clarity. Also if the final objective is always the reduction of extreme poverty, SDGs try to reach that by focusing on different dimensions, which are interconnected but not directly water (SDG 6), energy (SDG 7), sustainable cities (SDG 11), climate actions (SDG 13), strong institutions (SDG 16) etc.

1.2 Energy Transition

The energy sector itself is key to limiting global warming since it is responsible for 73% of global greenhouse gas (GHG) emissions (WRI, 2020). Most of the emissions come from fuel combustion, where the energy is used in industry, transport, and building sectors. To address this issue, energy transition is conceptualised and operationalised by many national governments, and international bodies like the International Energy Agency (IEA), and International Renewable Energy Agency (IRENA). It is most commonly defined extensionally and in a normative manner.

Traditionally, the policy approaches regarding the energy transition were guided by the security of supply, sustainability, and economic efficiency, often the security of energy being at the top agenda (Ang et al., 2015). Energy security can be defined as "the uninterrupted availability of energy sources at an affordable price.", according to the IEA. This definition has two dimensions: economic (affordable price) and technical (reliability). The original mandate of the IEA was to guarantee reliable and affordable energy supplies, it analyses current and potential risks for oil supply disruption, new security concerns with regard to gas, and improving system adaptability and resilience of the electricity sector (IEA). The energy sector is facing important structural changes which, of course, are reflected in changes in the practices of the IEA, as the paradigm of energy security varied importantly. OECD countries used to define energy security as the attainment of three objectives, security of supply, sustainability, and economic efficiency. While the World Energy Council prefers to talk about what they call the energy trilemma: security of supply, ecological sustainability, and energy justice. In both cases, it is fundamental to underline synergies and trade-offs between the different elements (Pastukhova et al., 2020).

Since 2010 and onwards, in addition to the traditional paradigms, sustainable development and growth have become key concerns. The two key objectives of security of supply and climate protection have been accompanied by the goals of sustainable development and a fair and equal supply of energy worldwide, promoted by the United Nations (The Sustainable Development Goals (SDGs) in 2015). Goal 7 (SDG 7) is to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030. Sustainable development is very much connected to the issues of energy justice and energy poverty, but also environmental protection. Indeed, energy security, economic efficiency, sustainability, and climate neutrality are contemporary guiding paradigms for policy approaches regarding energy transitions.

To tackle SDG 7 reaching universal energy access in SSA is capital, as a great percentage of people who do not have access to electricity live in SSA. Furthermore, SDG 7 has major synergies with other SDGs, notably solar technologies could provide huge progress with SDG 11 on various aspects: transport and waste management among others[1]. Other synergies are also present, with SDG 4, 40% of workers in the Solar PV sector and 32% in the renewable energy sector are women (IRENA, 2022b), SDG 6 (energy-water nexus). Other synergies can be found with SDGs 1 to 13 (Fuso Nerini et al., 2018).

1.2.1 The Context of Global North

Energy Transition in the global north is strongly linked to climate. However, If the trajectory observed prior to 2015 had been sustained, a projected rise of 3.5°C by the year 2100 would have ensued. Transition is, therefore, necessary to increase the share of renewables and enhance efficiency from the perspective of mitigating climate change. (IEA, 2022a). Over the last 20 years, renewable energy has increasingly spread as a tool to mitigate climate change (Mulopo, 2022) and increase energy security. (IRENA, 2022a). Other components of energy transitions are shown in Table 1, below:

[1] Transport and waste management are huge problems in SSA, according to the UN 1 dweller out of 3 has access to convenient public transportation, on average.
Waste management is also central as bad waste management could lead to floods in river-rich zones such as central Africa. The wastes will deposit into the bed of the river hindering its capacity for water absorption. This will eventually result in floods.

Efficiency	*Renewables*	*Fuel Switch & CCUS*	*Other*
Buildings	Wind	Phase-out fossil fuels	Batteries
Power	Solar PV	Nuclear	Storage
Light industry	Biofuel transport	Fuel switch inc. hydrogen	Behavioural change
Cars & Trucks	Other renewable power	Electric vehicles	Resource efficiency
Heavy Industry	Other renewable end-uses	CCUS power	Power system flexibility
Air conditioners	Hydro	CCUS industry	(inter)continental grids
Aviation and shipping			UHVDC, UHV, HWLT
Smart grid, smart meters			

Table 1 Components of the energy transition. Sources: IEA, World Energy Outlook 2019, Pastukhova, M., & Westphal, K. (2020). Governing the global energy transformation. In *Lecture notes in energy* (pp. 341–364). Springer International Publishing

Recently, affordability has also been a concerning issue following the war in Ukraine showing that electricity prices could spike at any moment. The war in Ukraine contributed to changes in the paradigm of energy security in Western countries. Western countries had to cope with the absence of the Russian gas supply due to sanctions imposed upon Russia, following the invasion of Ukraine (European Commission, 2022). The main challenge to energy security in Europe is to reduce drastically the role of fossil fuels in energy production and, at the same time, provide reliable energy services. According to the IEA, to address energy security Western countries should build resilient and clean supply chains. Enhance climate resilience of infrastructures so that they can resist the extreme events which are likely to happen if the 1.5° threshold is exceeded; Engage private actors and provide the market with tools to address market failures, as market mechanisms are one of the most effective ways to modify people's behaviour. The situation in Ukraine illustrates this perfectly, as electricity prices increased, we simultaneously observed a reduction in consumption. Also, we should invest in flexibility, because with a higher penetration of renewables in the grid flexibility will be central to handle demand and supply (IEA, 2022a). Last but not least, energy efficiency. According to the projection of IRENA, energy efficiency is going to represent 25% of emissions reduction in 2050 (IRENA, 2022a).

1.2.2 Energy Transition in Sub-Saharan Africa

African countries are particularly likely to be strongly impacted by climate change despite having some of the lowest footprints worldwide, as underlined by the IPCC (IPCC, 2022). For this reason, all the countries in the continent signed the *Paris Agreement* (IPCC, 2022). Some countries in SSA renewed their will to reduce carbon emissions during COP27, notably through the African Carbon Market Initiative (ACMI). The initiative aims to allow governments, stakeholders, and communities to finance their clean energy projects through the Voluntary Carbon Market (VCM) through carbon credits (ACMI, 2022).

This is not the only reason explaining the diffusion of renewable energy (RE) in SSA. There are two more. First, RE can help handle the balance between demand and supply; second, it can provide energy where it is not present, making cities more sustainable by ensuring both security of supply and accessible costs and of course, reducing CO_2 emissions simultaneously. Moreover, the solar potential of Africa is enormous (Abdelrazik et al., 2022). This is especially true for Northern and Southern Africa as we can observe in Fig.1. Particularly, for DRC, the highest potential is observed in the northern and southern parts of the country. This is most likely due to the proximity.

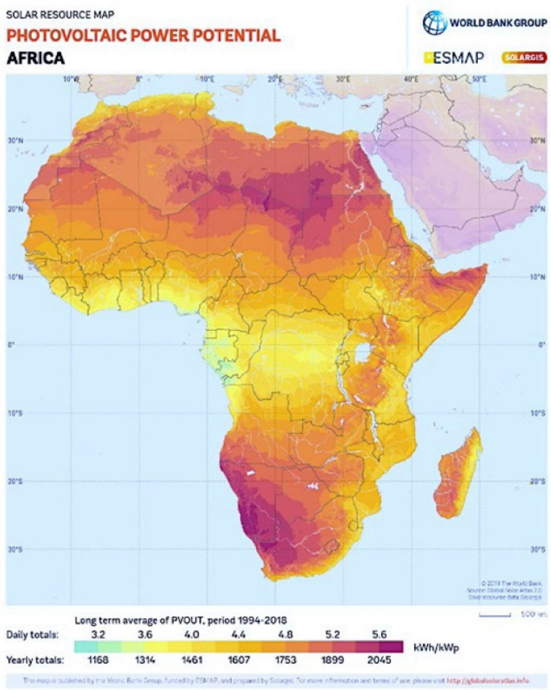


Figure 1 Photovoltaic power potential of Africa. Sources: World Bank, ESMAP

Energy security is a major challenge in SSA but the issues behind this challenge vary from Western European countries. Electricity generation in SSA is characterized by ageing and defective energy infrastructure due to severe under-investment in the sector (IEA, 2022; IRENA, 2021). Between 2020 and 2022 only 1.5 of global investments in renewable technology were destined to SSA (IRENA, 2023). Prices are another important factor related to energy security. For electricity prices to be affordable in SSA, countries are obliged to subsidise the energy sector, but with the demography of African countries this "subsidy burden" is set to double within 2030. Tariff reforms are needed to create a more efficient subsidy system which could only target people in need, this would also help utilities not to operate in debt distress and avoid default. Low prices are needed to attract consumers but at the same time, those prices are not profitable enough for utilities to repair their costs (IEA, 2022). For this reason, in most countries of SSA, we typically observe situations of natural monopoly in this sector (SNEL for DRC, ESKOM for South Africa etc.). The examination of these facets will be expounded upon extensively in section 5 (Discussion).

Security in SSA is not only a question of reliability but also a matter of access but also affordability and reliability (IEA). Most countries are dependent on domestic oil, gas coal or imported fuel. In the first case, this could generate Energy Security issues due to the necessity of reducing CO_2 emissions. In the second case, it could expose countries to the effects of the volatility of prices in the international market. As we can observe in Fig. 2, nowadays, electricity generation is mainly composed of gas, oil, and hydro. At present 43% of the African population lacks access to electricity, and most of them live in Sub-Saharan Africa (SSA). (IEA, 2022b). The African Union declared the intention of achieving universal energy access by 2030.

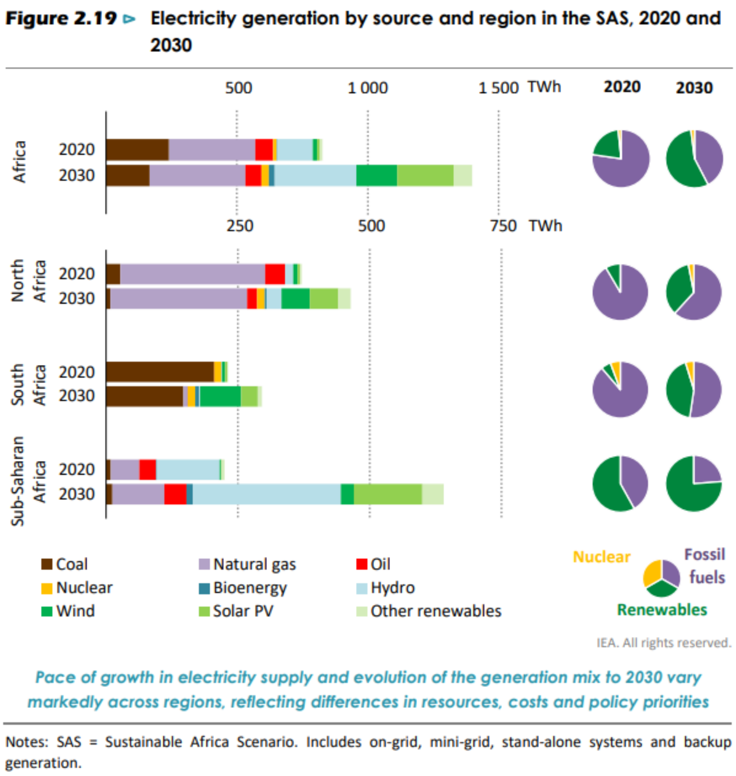


Figure 2 Electricity generation by source and region in the SAS, 2020 and 2030, IEA, *Africa Energy Outlook*

Fig. 2 also highlights that, according to the projections of IEA, most of the added capacity within 2030 will consist of hydro, solar, and, to a lesser extent, wind.

Increasing generation capacity through solar allows for avoiding transmission costs and grid expansion costs. These costs are often prohibitive in remote and/or rural areas. Longe et al. estimate this cost at $20,000/km for an 11 kV line cost alone in SSA, without counting the other components that are required. (Longe et al., 2014). Yet, increasing the capacity of hydro will require grid expansion. Whereas gas, in the Sustainable Africa Scenario (SAS) of the IEA, will play a central role in flexibility.

1.3 Energy transition pathways

There is a consensus about the fact that the energy transition is highly needed to mitigate climate change. Arguably, the pathway to carbon neutrality is far from being consensual. There are diverse socio-technical imaginaries that are articulated and supported by policy, science, and society with their way of enforcing and imagining carbon neutrality.

1.3.1 The Global North

In the global north, the socio-technical imaginaries mainly come from the industry and are echoed by policymakers who emphasise technologies and businesses such as «modernization and techno-economic development" where energy transition is an opportunity to modernize the energy systems. Similarly, a "green economy» entails markets, business, and job creation opportunities in the carbon-neutral economy where the paradigm of economic growth is coupled with sustainability and climate change mitigation again with a dominant techno-centric imaginary (Carvalho et al.,2022; Genus et al., 2021)

Alternatively, «energy citizenship», energy transition is framed as a process in which «individuals and communities become active agents of socioecological transitions» (Carvalho et al., 2022). The structure is typically bottom-up, decentralized, and distributed energy plays a central role, alongside Energy Communities (EC). Specifically, within the European Union, the Clean Energy for All Europeans Package (CEP) (European Union, 2019) for the first time has recognized the energy communities and offers an enabling legislative framework for collective citizen participation in the energy system (European Parliament, 2019). Here, social dimensions such as energy democracy as well as social capital development, and community empowerment are strongly emphasised by the SSH (Social Sciences and Humanities) community to succeed in the energy transition (Bielig et al., 2022). Furthermore, the SSH community, though not mentioned in the policy frameworks, further frames an alternative imagination with a focus on a radical reorganization of society with practices and cultural changes.

1.3.2 Socio-technical imaginaries for the Global South

Considering the socio-technical imaginaries of communities is fundamental for a project to be successful in the Global South (Cloke et al., 2017). Cloke Et al. highlighted that most community energy projects are managed with a top-down approach. Usually, an entity resulting from the government, or an international organization has the upper hand and imposes its vision, while the local participants are most likely not involved in the design part. The education provided is essentially focused on the overall advantages of solar technologies and not on how this could improve their livelihood (Cloke et al., 2017). The majority of the Imaginaries coming from governments and international organizations focus on technical aspects, especially scale (Simmet, 2018). Various discussions took place around which could / should be the optimal scale for a project (Cloke et al., 2017). After reviewing different successful projects Cloke et al. conclude that the perfect scale appears to be the social scale that allows local participants to play an active role in the conception of the project. The project should be therefore shaped upon the community and not conversely, both from the technological and the financial point of view. A bottom-up approach that considers the aspirations and needs of the community should be adopted in the first place. Policy support is central for projects to succeed, nevertheless, the community's needs have to be at the centre of the picture (Cloke et al., 2017).

1.3.2.1 The case of the Masaai

(Adornetto, 2022) conducted a qualitative investigation employing interviews with the Masaai community in Tanzania to explore their perceptions and attitudes toward solar energy and electricity. The study aimed to delve into the Masaais' conceptualizations and expectations concerning these energy resources. Drawing from the findings by Adornetto (2022); Cloke et al. (2017) illustrated that the Masaai community exhibits a distinct interest in the services facilitated by electricity, rather than electricity itself. Specifically, interviewees expressed a desire for lighting within their households and torches to assist with livestock management. Concurrently, there was a pronounced reluctance to embrace changes that may disrupt their traditional way of life. The Masaai interviewee highlighted that the advent of electricity often coincides with the introduction of automobiles and the development of urban infrastructure, such as streets. These perceived consequences of electrification were regarded as potentially detrimental to their customary lifestyle and cultural norms. Consequently, the community exhibited a cautious stance towards embracing electricity as they sought to preserve their cherished traditions and maintain the integrity of their socio-cultural identity. These findings shed light on the complexities inherent in the adoption of modern energy resources within indigenous communities. It underscores the importance of understanding the nuanced perspectives and priorities of such communities when introducing new energy initiatives. Policymakers and energy planners must take into account the intricate interplay between energy development and socio-cultural dynamics to ensure that sustainable energy transitions are aligned with the values and aspirations of the affected communities. The research by Adornetto (2022) contributes valuable insights into the delicate balance that must be struck between energy service provisioning and the preservation of indigenous ways of life.

1.3.2.2 The case of Senegal

Simmet (2018) identifies two main scenarios for Senegal. One relies on a technology-led idea of development. This idea consists of considering that to improve development and electrification in SSA, especially in rural zones of Senegal, the only thing needed is technology, if the desired level of electrification is not attained it is because funding is lacking. This is typically the vision "imported" by International Organizations and NGOs, as well as the view supported by donors, according to Simmet.

The second one is a "locally embedded approach", people are at the centre of the project and electrification is conceived according to the value people allocate to electricity. Also, this vision considers the cultural specificities of people and tries to analyse the context to integrate the elements of the project that are likely to involve people in the project.

Simmet highlights with the Senegalese example that often "experts" and tenant of legitimate knowledge are somehow imposing their view, which is based solely on the technological aspect of the problem.

Technocratic views are therefore imposed on people as this is what the donors perceive as the "right choice" while the resultant projects are not necessarily "what we asked for" (Simmet, 2018).

To sum up, the energy transition in SSA, should not be limited to a technology-driven approach but should enable people to come up with new alternative inclines to be a better fit for SSA societies. That being said, the correlation between electricity access and development is positive (Rateau, 2021) and there is empirical evidence of other positive experiences in the field in different domains such as health (Moner-Girona et al., 2021), and gender equality (Winther & al., 2017), among others. We can conclude that Simmet's paper should not be interpreted as a firm opposition to technology, but rather as an invitation to consider other factors along with technology. Nevertheless, Matinga & Annegarn (2013) state that electricity can be interpreted as a negative element quoting the example of a woman who felt excluded and isolated from society as the number of appliances worked as a marker of social status. She did not have a TV and electricity could highlight this kind of inequality. Yet, I think that the overall benefits of electricity overshoot this kind of inconvenience.

1.4 Energy Communities

Local communities are now seen as an instrument for developing these low-emission economies through decentralized production and consumption of renewable energy. Indeed, decentralised systems are said to present several advantages over centralised ones, including reduced costs for distribution and transmission systems, and reduced grid power losses (Reis et al., 2021; Sims et al., 2007).

1.4.1 Energy Communities in the Context of Global North

The concept of energy community has been present in literature since the 70s. It first started as an alternative way to produce energy, against large-scale and centralized energy systems (Scapin, 2022). We do not have yet a clear definition of EC as they can take different shapes and several configurations but recently the EU made an effort to define EC legally.

According to Walker and Devine-Wright "Community energy refers to a wide range of collective energy actions that involve citizens' participation in the energy system. Community energy projects are characterised by varying degrees of community involvement in decision-making and benefits sharing" (Walker and Devine-Wright, 2008). They may describe a community limited by a geographical location or a community of interest (Walker and Devine-Wright, 2008)." Democracy is another central element to EC, as underlined by Roberts et al. (2019) "Energy communities can be understood as a way to 'organise' collective energy actions around open, democratic participation and governance and the provision of benefits for the members of the local community". When talking about EC many different nomenclatures can be found in the literature; in the texts from EU two different nomenclatures are present "citizen energy communities" in the revised Internal Electricity Market Directive (EU) 2019/944 (European Parliament & Council of the European Union, 2019), "renewable energy communities" in the revised Renewable Energy Directive (EU) 2018/2001 (European Parliament & Council of the European Union, 2018).

ECs are spreading all over Europe, we can count more than 9,000 ECs across Europe, according to the European Commission[2]. Many other definitions of EC are available but exploring all of them in this short note would be complex, therefore we will focus on common characteristics of EC. Defining them according to these will be easier. Ambole & al. (2021) provide a list of common characteristics which is the result of the analysis of 20 different definitions of EC (all of them in the Western context). Those characteristics are Community involvement and cooperation, Open and Voluntary Participation, Democratic governance, Institutional support, Decentralised renewable energy, and innovative technologies.

Another important element that has to be highlighted are drivers of the adoption of EC. According to Caramizaru & Uihlein (2020), most ECs are to be found in high-income countries in Northern-Western Europe. "The most common drive is the motivation to invest in community energy infrastructure such as

[2] https://energy.ec.europa.eu/news/focus-energy-communities-transform-eus-energy-system-2022-12-13_en#:~:text=However%2C%20they%20are%20still%20a,in%20operation%20across%20the%20EU.

renewables installations, district heating, energy efficiency systems, or charging infrastructure. The ambition to protect the environment and the desire to be socially, ecologically, and economically self-sufficient is particularly prevalent among housing communities and bio-villages“. We could conclude that the main drivers are economic savings, sustainability, improved sense of community (which would affect the social acceptability of the technology), Energy justice (CE are proven to "better distribute benefits among residents"), and energy policies. To sum up, we could say that on average, the typical profile of an individual who participates in EC in western-northern Europe is a person with a certain degree of knowledge and awareness of the environmental situation; taking part in EC is then a reaction to their "strong ethical and environment commitment" (Soeiro, 2020).

The same might not be true in SSA as Energy Communities are answering to different needs in the two contexts.

1.4.2 Energy Communities in Sub-Saharan Africa

Very few energy communities can be found in SSA and there is no legal framework to support their implementation. The main difference relies on the purposes. If in the EU the main drivers are economic savings, sustainability, improved sense of community, energy justice, and energy policies (Ambole, 2021; Caramizaru & Uihlein, 2020), in SSA the situation is different. Economics savings are not a priority in the sense that ECs in the EU represent an alternative to a system that is already present – and working - while in SSA they are an alternative to a development method which leaves many people unattended and without any access to electricity. Even if sustainability is implied in the process, it is probably not the main driver for the implementation of EC from the societal point of view. As highlighted by Ambole et al. (2021) the few ECs present in Africa try to solve underlying problems such as health improvement, and poverty reduction. Energy policies are not supporting the development of EC in Africa. Sense of community is a bit tricky as we should define what is a community and defining a community implies defining its geographical boundaries. Whereas this could be easier in SSA, as population density is lower it might be trickier in the EU, depending on the legal framework of every country.

To sum up, in Sub-Saharan Africa, energy communities diverge from the paradigms observed in the global north, exhibiting distinct priorities and objectives. The primary objectives within these communities are twofold: the attainment of more affordable electricity and the augmentation of energy access. These objectives are intrinsically intertwined, as energy communities serve as pivotal enablers for enhanced energy accessibility within the region.

Energy communities in SSA are closely aligned with the notion of energy access, presenting an opportunity for previously disenfranchised populations to gain electricity access. This is particularly significant for those residing in remote rural areas, situated far from the conventional power grid. Substantially more cost-effective than traditional grid extensions, energy communities offer an accessible alternative. The International Energy Agency (IEA) reports that approximately 373.76 million people in rural SSA currently lack electricity access (Fig. 3). In this context, energy communities rely on the deployment of solar panels, which can be readily installed in remote locales at a comparatively modest expense when compared to extensive grid infrastructure.

Moreover, energy communities have the potential to furnish reliable and modern energy services, engendering notable benefits for both governmental bodies and local authorities. Modern energy is intimately related to efficiency, and this latter can help mitigate demand growth, consequently, lowering the bill (IEA, 2022). When effectively managed, these ventures can prove to be economically advantageous (Ambole et al., 2021). Concurrently, local communities stand to gain substantial benefits, as they actively participate in these energy projects, consequently influencing the energy system according to their specific needs (Ambole et al., 2021).

In conclusion, energy communities in Sub-Saharan Africa are characterized by their distinctive priorities and close ties with energy access. By facilitating the provision of affordable and reliable electricity, these communities represent a promising avenue for fostering equitable energy distribution and driving socio-economic development in the region.

Scholars argue that one of the main barriers to electricity access in SSA is the focus on large projects and the predominant top-down approach. In SSA state organization is often centralized which means that municipalities and other "decentralized entities" have little power and even little projects need validation from the government, which will lead to difficulties in bureaucratic organizational structures. In this case, state support manifests as a hindrance to a fluid implementation. Stakeholder engagement is key, but no incentive is provided to develop and entertain this engagement (Ambole et al., 2021).

In light of the above, EC could be a great tool to develop electricity access in SSA but new mechanisms (liberalization of the market, effective financial model allowing the reduction of energy poverty and at the same time allowing companies' activities to be sustainable, among others, supporting energy policies) must be introduced to allow ECs to develop further in SSA. Yet, the number of ECs is growing as they are "gradually emerging as a pathway towards sustainability and resilience for millions of households in the region" (Ambole et al., 2021).

1.5 Research questions, aims, and objectives

In light of the clearly defined market potential and need for electrification, there is an ongoing debate surrounding the feasibility of implementing resilient systems, like microgrids, in Sub-Saharan Africa, particularly in regions facing challenges such as a lack of income and skills needed to maintain such systems. The uncertainty regarding the techno-economic viability of renewable microgrid projects in diverse rural contexts has led to hesitation among project developers and investors. Key questions remain unanswered, such as whether a reasonable return on investment can be achieved within a specific timeframe, and how to reduce the cost of capital in SSA, where elevated perceived risks (Agutu et al., 2022) contribute to high rates. Additionally, addressing the challenge of establishing a substantial customer base remains critical in regions where population distribution is notably sparse.

To address this lack of evidence, this study sets out to answer the following main research question:

What are the potential energy, economic, and environmental impacts of micro-grid rural energy communities that utilize renewable technologies in the Democratic Republic of Congo (DRC)?

To answer this question, this thesis' overall aim is to investigate and evaluate the potential techno-economic and environmental performance of a micro-grid via multiple scenarios in different rural energy community typologies that exist in the Democratic Republic of the Congo.

This aim is achieved by meeting the following research objectives:

To conduct a literature review on Energy communities, techno-economic analyses, energy access, energy mix, and CO_2 reduction.

To collect data to model energy community typologies, electricity demand, and load profiles

To develop a modelling framework to design a Mini-Grid (MG) model for rural electrification of energy community typologies and run multiple scenarios for techno-economic analysis, and CO_2 analysis of community typologies in SSA/DRC.

To examine various scenarios across different rural energy community typologies, present in the country.

To perform a comprehensive techno-economic and CO_2 analysis, with a specific focus on the Democratic Republic of the Congo (DRC).

To demonstrate the potential contributions of solar energy and renewable energy communities in advancing electrification and facilitating access to affordable, reliable, sustainable, and modern energy for all.

To indicate and discuss possible implications and recommendations for policymakers tailored to Sub-Saharan Africa and the unique context of the DRC.

The main contributions of this master thesis will be twofold:

To contribute to the existing limited knowledge by generating more comprehensive understandings and insights into a broader range of locations and contexts in Sub-Saharan Africa, with a particular emphasis on the DRC on renewable energy implementation and its potential socio-economic implications. Indeed, concerning LCA analysis and techno-economic assessments, most research focuses on top economies (Algeria, Morocco, Nigeria, South Africa, and Egypt)(Karkour et al., 2021).

To contribute to the existing data scarcity in the context of energy-related research in Sub-Saharan Africa. Notably, the region faces limited availability of comprehensive and reliable data in this domain. (Mulugetta et al., 2022) Existing research in this area predominantly concentrates on select countries, which further varies depending on the specific research topic. For instance, investigations into 100% renewable energy systems are mainly confined to countries such as Morocco and Nigeria, as evidenced in the work of Oyewo et al. (2023).

2. Literature review

2.1 Energy context in Sub-Saharan Africa

In the next section specificities of energy consumption in SSA will be analysed in the first place. Secondly, the focus will shift to energy communities (ECs). Thirdly we will review literature relating to the techno-economic analysis of minigrid (MG) in SSA. Finally, we will provide a state of the art of current LCA analysis (focusing solely on CO_2 emissions) in SSA.

2.1.1 Electricity access

Electricity access in SSA varies substantially across the regions. Figure 5 allows us to picture an overall view of electricity access in SSA, in 2020. On average, 49% of people living in SSA have access to electricity. A closer look at the figures would explicitly how heterogeneous the situation is in SSA. The average in Central Africa is 22%, this is most likely due to the low values recorded in Central African Republic (5%), Chad (8%), and the Democratic Republic of the Congo (9%).

In East Africa, the average rises to 46%, except for Burundi (10%) and South Sudan (7%) the average electricity access is higher than 25% in every country, which is not ideal but is an improvement compared to the situation in central Africa.

In West Africa, the average is higher, as it is situated at 60% but this does not mean that the situation is better. The situation is very diverse within the subcontinent, values range from 14% (Niger) to 95% (Cape Verde). Despite providing, a general picture of the situation in terms of electrification, the explanatory merit of the average in this context is limited, at least. The average cannot represent the specificities of every country related to electrification (population density can vary considerably from one country to another and tend to be higher for smaller countries which makes electrification less challenging, in terms of connections and electrification of rural households, the so-called "last mile electrification"(Chakravorty et al., 2016), this is typically the case of Cape Verde. Other countries are islands and are consequently subjected to the technical constraints specific to the islands. Namely, the dimension of their grids and, subsequently, the energy they can host. Furthermore, from the commercial standpoint, energy systems are typically financed by a small share of "big" customers which are usually commercial and industrial, since residential customers tend to have low bills. (Taneja, 2018). Taneja (2018) illustrated that within the Kenyan context, residential consumption, albeit constituting the vast majority of the customer base at 94.6%, accounted for only 27.8% of the total consumption. While commercial and industrial sectors, although accounting only for 5.36% of the customer base represent 55.4% of the total consumption. It is fair to suppose that for islands, the share of commercial and industrial customers – and therefore the available financial resources - would be lower.

Due to its higher economic and infrastructural development, South Africa is often considered as a whole and not related to other regions in the continent. South Africa is incurring an important energy crisis. Mainly linked to the internal crisis on the national utility, ESKOM, this latter could not renew its fleet which is composed of a large number of run-down power plants, on top of that corruption was endemic in ESKOM. The infamous case of knee guards[3] it's just one of the examples that illustrate the situation. Nowadays, South Africans have to comply with severe load shedding, leading to an availability of electricity that could be lower than 10 hours a day.

IEA regroups all of the other African countries under the regional body called "other Southern countries", as in the other regional group, heterogeneity is extremely elevated. The average for the group is 37% but values range from full access (for Seychelles and Mauritius) to 11% of Malawi.

[3] Knee guards were bought from ESKOM at an extremely high price comparing to their market value (R80,000 vs 200,000) said former CEO André de Ruyter.
https://www.rtl.be/actu/monde/economie/electricite-eskom-geant-sud-africain-aux-pieds-dargile/2023-03-02/article/529136

Furthermore, for every regional zone, a huge difference can be noticed when focusing solely on rural or urban areas. The average of 49% would rise to 79% in urban settings and decrease to 28% in rural settings. The same pattern would be observed in every country, with some notable exceptions, namely Seychelles and Cape Verde. Showing that if urban electrification can be more or less challenging according to the country, rural electrification is a shared challenge in the sub-continent.

In DRC more specifically, electricity access was 9% on average, in 2021 (IEA). Electricity access was 19% in urban settings and less than 1% in rural settings. Highlighting once again, the complexity – and the need - of rural electrification. The scarce development of the national grid certainly has an impact on the low level of electrification in DRC.

Source: IEA, World Energy Outlook-2021

Electricity Access in Africa

	Proportion of the population with access to electricity							Population without access (million)
	National					Urban	Rural	
	2000	2005	2010	2015	2020	2020	2020	2020
Africa	**36%**	**40%**	**43%**	**50%**	**56%**	**83%**	**36%**	**584**
North Africa	**91%**	**97%**	**>99%**	**>99%**	**>99%**	**>99%**	**>99%**	**<1**
Algeria	98%	98%	>99%	>99%	>99%	>99%	97%	<1
Egypt	94%	98%	>99%	>99%	>99%	>99%	>99%	<1
Libya	>99%	>99%	>99%	>99%	>99%	>99%	>99%	<1
Morocco	72%	90%	99%	>99%	>99%	>99%	>99%	<1
Tunisia	95%	>99%	>99%	>99%	>99%	>99%	>99%	<1
Sub-Saharan Africa	**24%**	**28%**	**33%**	**40%**	**49%**	**79%**	**28%**	**585**
Central Africa	**15%**	**16%**	**19%**	**22%**	**22%**	**42%**	**4%**	**115**
Cameroon	46%	48%	52%	62%	63%	93%	22%	10
Central African Republic	1%	2%	2%	3%	5%	9%	2%	5
Chad	2%	4%	4%	8%	8%	32%	<1%	15
Congo	21%	23%	39%	44%	48%	66%	10%	3
Democratic Republic of the Congo	7%	8%	9%	9%	9%	19%	<1%	82
Equatorial Guinea	65%	66%	66%	67%	67%	74%	47%	<1
Gabon	31%	46%	60%	82%	91%	>99%	11%	<1
East Africa	**10%**	**16%**	**21%**	**32%**	**46%**	**79%**	**35%**	**168**
Burundi	4%	5%	5%	9%	10%	69%	<1%	11
Djibouti	46%	48%	50%	42%	42%	54%	<1%	<1
Eritrea	17%	25%	32%	41%	50%	96%	18%	3
Ethiopia	5%	16%	22%	34%	48%	96%	35%	59
Kenya	7%	10%	14%	44%	78%	>99%	69%	12
Rwanda	6%	8%	10%	26%	55%	76%	51%	5,8
Somalia	5%	9%	14%	29%	35%	32%	38%	10
South Sudan	n.a.	n.a.	n.a.	5%	7%	13%	6%	10
Sudan	30%	31%	36%	43%	47%	75%	32%	23
Uganda	4%	10%	14%	19%	26%	65%	13%	34
West Africa	**34%**	**39%**	**44%**	**50%**	**60%**	**92%**	**30%**	**163**
Nigeria	41%	48%	52%	58%	68,2%	99%	36%	66
Benin	16%	23%	26%	31%	31%	57%	7%	8
Cote d'Ivoire	50%	52%	59%	63%	78%	>99%	55%	6
Ghana	45%	52%	65%	76%	85%	93%	74%	5
Senegal	31%	42%	57%	62%	70%	95%	47%	5
Togo	12%	18%	22%	33%	46%	83%	19%	5
Burkina Faso	13%	9%	14%	19%	21%	69%	<1%	16
Cape Verde	68%	75%	81%	87%	95%	96%	93%	<1
Gambia	18%	26%	34%	45%	62%	79%	35%	<1
Guinea	16%	20%	25%	29%	44%	86%	19%	7
Guinea-Bissau	11%	12%	12%	18%	39%	73%	12%	1
Liberia	2%	2%	3%	16%	29%	48%	8%	4
Mali	13%	15%	27%	36%	52%	98%	16%	10
Mauritania	22%	18%	35%	40%	47%	85%	<1%	3
Niger	7%	8%	9%	11%	14%	71%	2%	21
Sao Tome and Principe	53%	55%	57%	59%	77%	>99%	12%	<1
Sierra Leone	9%	11%	12%	20%	22%	51%	<1%	6
South Africa	**77%**	**78%**	**84%**	**92%**	**95%**	**96%**	**93%**	**3**
Other Southern Africa	**14%**	**17%**	**22%**	**31%**	**37%**	**69%**	**16%**	**135**
Angola	12%	17%	27%	36%	45%	64%	7%	18
Botswana	22%	40%	45%	53%	60%	75%	23%	<1
Comoros	30%	35%	40%	69%	70%	89%	62%	<1
Lesotho	3%	10%	20%	32%	46%	76%	33%	1
Madagascar	8%	15%	18%	21%	27%	58%	8%	20
Malawi	5%	7%	9%	11%	11%	46%	4%	17
Mauritius	>99%	95%	>99%	>99%	>99%	>99%	>99%	<1
Mozambique	5%	11%	18%	29%	38%	73%	17%	19
Namibia	34%	34%	44%	45%	45%	69%	20%	1
Seychelles	50%	54%	58%	99%	>99%	>99%	99%	<1
Eswatini	25%	30%	35%	75%	76%	>99%	68%	<1
Tanzania	11%	12%	18%	30%	38%	73%	19%	37
Zambia	12%	20%	22%	31%	33%	71%	2%	12
Zimbabwe	40%	36%	37%	46%	53%	90%	35%	7

Figure 3 Energy access in Africa, IEA, 2020

2.1.2 Grid context

The development of the national grid in SSA reflects the heterogeneity ascertained in electricity access. Figure 4 shows that grid development is higher in West Africa and South Africa. Concomitantly, we can notice that grid development in Central Africa is meagre.

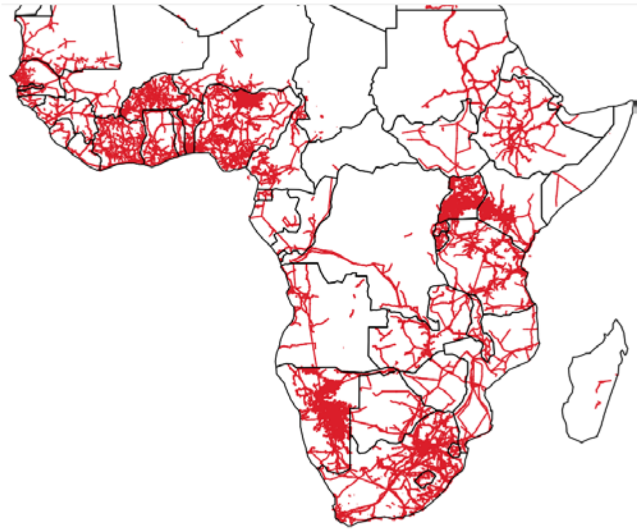


Figure 4 Grid in Sub-Saharan Africa (Data from Koulaki et al. 2020)

Looking at DRC more specifically, it can be observed in Figure 5 that the national grid only covers a small part of the country's surface. Corresponding to the South-west and the southern parts of DRC. We can also notice two small grids in the central part of DRC corresponding to the provinces of Tanganyika and Maniema. Essentially, the most densely populated zones in DRC (Flouriot, 2008).

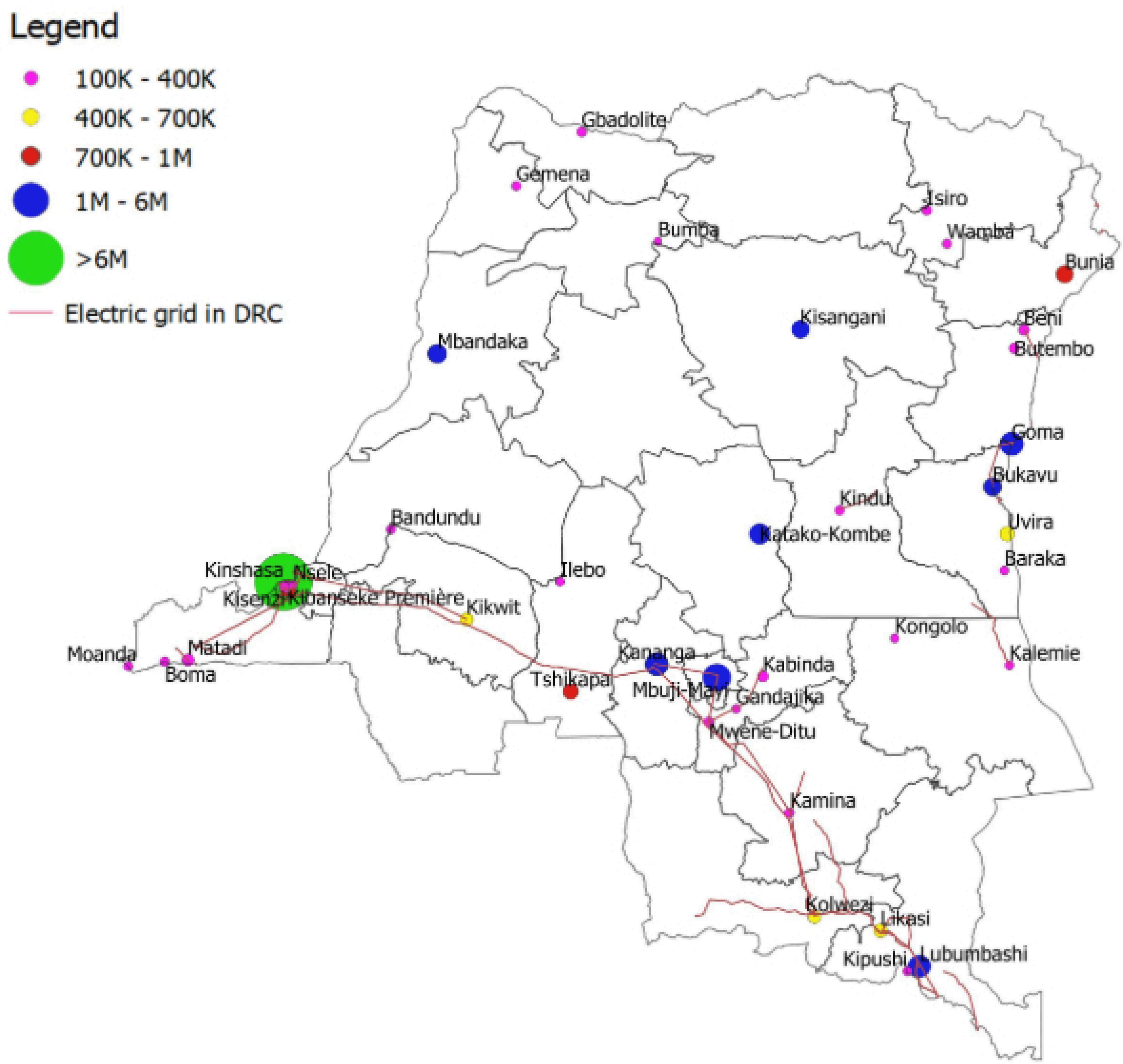


Figure 5 National grid of DRC (red line) and cities categorized by the amount of urban population in DRC. (Grid data adapted by the author from Koulaki et al. 2020. Towns with relative inhabitants added by the author, data adapted from UN-HABITAT and simplemaps.com). Please notice that the town with the lowest urban population (Bumba) present on the map has about 103,000 inhabitants, while the one with the highest urban population (Kinshasa) has more than 15 million inhabitants. While towns like Kananga, Kisangani, or Mbuji-Mayi have over one million inhabitants.

This configuration leaves several people without access to electricity, notably in the central parts of the country. Albeit being more sparsely populated the central and northern parts of DRC lack electricity access. The same situation replicates in the eastern part of DRC, with the difference that this latter is highly densely populated.

Moreover, the grid in Sub-Saharan Africa is often unreliable (J. T. Lee & Callaway, 2018), which implies that electricity access cannot be ensured even when connected to the grid. In DRC the grid is extremely unreliable. In 2022 some tests were held on the power system of Lubumbashi for three months. Tests resulted in a total of 1185 hours of shutdown of the electrical supply, which corresponds to more than a month and a half (Kibukila et al., 2022). Grid was therefore unavailable for more than half of the time, showing a crucial need for maintenance (Kibukila et al., 2022). The Total Energy Supply (TES) in DRC consists essentially of biomass. This latter accounts for 97% of the energy supply, other 3% is oil (IRENA, 2022c). Electricity in DRC is mainly produced via renewable energy, 99% is hydro, and 1% is solar (IRENA, 2022c). Despite a share of renewable extremely elevated in the electricity mix, supply is not nearly sufficient, this, conjointly with the failure of deteriorating material and overloaded equipment leads to important load shedding and reduced electricity access (World Bank, 2020). The World Bank conducted an in-depth analysis of SNEL's (*Société nationale d'électricité*) activities and identified the main reasons that caused power outages. 65% of power outages in DRC originated from load-shedding. 10% is overloading of equipment (saturation of lines). More than 9% is unknown. 6% is maneuvering on the grid, while the rest is essentially failures of cables and reduction in voltage.

SNEL plays a pivotal role in energy access in DRC, nevertheless, commercial losses are important, and debt is growing which makes it difficult to renew their asset or to purchase new ones (World Bank, 2020).

2.1.2.1 Financials of utilities

The financial situation of most utilities in SSA is critical. The World Bank is collaborating, through ESMAP, with the African Public Utilities Association (APUA). They made available different data on the financial and operational performances of public utilities in SSA.

In terms of financial performance, the great majority of utilities are facing significant debts. Out of the utilities analysed by the World Bank, only two utilities can claim a positive balance in their finances; Seychelles' and Uganda's (Taneja, 2018).

Furthermore, this condition has been worsened by COVID-19. Before COVID-19 many utilities in SSA were already struggling to leverage enough funding to finance both their operational costs and their debts. (Balabanyan et al., 2021). In DRC the national utility SNEL, which detains 90% of the transmission and distribution capacity of the country faced similar difficulties. In the case of SNEL, the financial situation can also be linked to the fact that with the ministerial decree of 2009. This latter imposes a relatively low tariff which corresponds on average to 7 cents (cts) per kWh (0.07$/kWh), the purpose of the low tariff is to allow electricity access at an affordable price to everyone. Furthermore, the majority of the new customers are low-consumption individuals who do not account for the majority of consumption, despite making up a sizable portion of the customer base. As a result, they are not very significant from a commercial standpoint, as they would not generally use large amounts of energy. In addition, the energy tariffs are low, as reported above, due to legal enforcement[4] (World Bank, 2020).

COVID-19 had a major impact on the financials of utilities in SSA. The World Bank claims that this impact's significance stems from the fact that it had an impact across five distinct fields (Balabanyan et al., 2021). The authors enumerate those impacts as follows. In the first place a macroeconomic shock reduced the GDP of countries and, consequently, the overall productivity. Secondly, a currency shock altered the price of imported goods, especially imported oil for fuel generation. Thirdly, the lockdown led to a reduction in the - already relatively low - energy demand in SSA. Fourthly, the lockdown implied other reductions in the demand (such as cancellation of flights, and therefore the on-utilization of airports, jointly with the closing of other important commercial and industrial users), which triggered a sort of "negative multiplier effect" which reduced demand, and therefore the revenues of utilities. In the end, all of the aspects analysed above had an impact on people's ability to pay (Balabanyan et al., 2021). The general shutdown would impact significantly people's revenue, especially in Sub-Saharan economies characterized by a significant degree of informality.

2.1.3 Characterizing consumption in Sub-Saharan Africa

Electricity demand in SSA is extremely minimal. Per capita electricity demand in SSA corresponded to 170 kWh/yr in 2020, according to the IEA (IEA, 2022). For DRC specifically, per capita consumption is 104 kWh/yr (Enerdata, 2021)[5]. Compared to over 6000 kWh/yr on average for Europe (World Bank). Nevertheless, electricity represents a modest proportion of the overall energy consumption in Africa. In DRC, electricity constituted less than 5% of Total Final Consumption (TFC), according to the IEA[6].

[4] ARRETE MINISTERIEL n° 005/CAB/MIN-ECONAT&COM/2009 du 7 mars 2009 portant fixation des tarifs de vente d'énergie électrique par la SNEL pour ses abonnés haute tension, moyenne tension et basse tension.
[5] https://www.enerdata.net/estore/energy-market/congo-dr/
[6] IEA, Africa data explorer , https://www.iea.org/regions/africa

Biomass addresses more than 90% of TFC, another small percentage is covered by oil products (essentially diesel generators used for backup) as per the IEA.

The low rate of appliance ownership can contribute to explaining the low energy demand, especially in rural areas. That being said, demand for appliances is hard to forecast in rural SSA, as illustrated by Lee et al. (2016), the authors made a survey in rural Kenya to assess the desired ownerships of households connected to the gris, to solar home systems and off-grid households. The desired high-wattage appliances in rural Kenya resulted mainly in television and iron for the three kinds of households. Contrary to what we could think, aspirations of households – in terms of ownership – may differ from the logic of "*if you build it, they will come*" (i.e. If appliance availability broadens, people will "come" and buy them) (K. Lee et al., 2016).

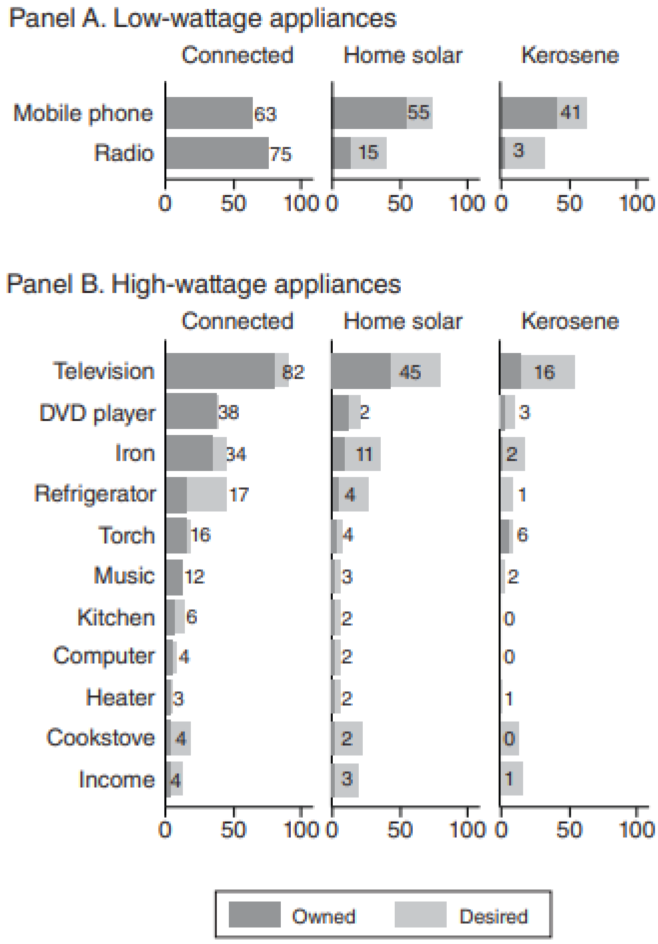


Figure 6 Owned and desired appliances in rural Kenya. Source : Lee et al. (2016)

Taneja addressed the topic of low demand focusing on the case of Kenya, but his conclusions can be extended to SSA in general as similar trends have been observed across the totality of the subcontinent (Taneja, 2018). In his paper, the author showed that electricity consumption did not grow between 2009 and 2015. Despite the larger availability of appliances, the latter lowered; which illustrates that increasing ownership of appliances might not be sufficient to stimulate demand growth (Taneja, 2018). Especially in rural settings where demand tends to be lower compared to urban ones (IEA 2022, Taneja 2018), as the first has in general more restricted access to electricity, as shown in Figure 3. Furthermore, there is uncertainty pertaining to whether people will be able to afford electrical appliances or not (Sackey et al., 2022). This uncertainty adds additional complexity to the task of estimating energy demand. Identifying precisely the needs of communities is primordial to provide them with electricity. In order to do that, and to estimate precisely future energy demand, considering latent demand is central (Sackey et al., 2022).

Latent demand is defined as follows by Sackey et al. (2022): "would be present if accessible infrastructure and adequate techno-economic conditions to supply electricity were available" (Sackey et al., 2022).

Calculating latent demand would fall beyond the scope of this work, yet it is something that has to be accounted for whenever considering electricity consumption in Sub-Saharan Africa. Various challenges are yet to be faced, notably concerning how to address data scarcity. To forecast latent demand precisely data availability is pivotal (Sackey et al., 2022). In the context of energy planning the absence of latent demand estimation could lead to underestimating the need of the system. This is particularly negative on the grid but it may engender several issues also from the PV supply standpoint (Sackey et al., 2022).

Overestimating the system could lead to an additional cost per Wh that would vary according to the entity of the overestimation. (Louie & Dauenhauer, 2016). The additional cost has been estimated to be between 1.92 $/Wh and 6.02 $/Wh. Simultaneously, an underestimation of the system would reduce the reliability of the system. (Louie & Dauenhauer, 2016).

2.1.3.1 Electricity theft

Another element characterizing electricity consumption in SSA is electricity theft. In fact, due to the deficit in utilities' ability to provide – reliable – electricity and other socio-economic factors such as unemployment, some people consider electricity theft as a strategy to cope with shortages and disruptions (Depuru et al., 2011). In this case, people are more likely to directly steal power from utilities by tampering with energy meters and/or wires (Depuru et al., 2011).

Electricity theft is a diffused practice in the global South due to the reasons mentioned above. However, several negative effects can be linked with electricity theft and non-technical loss in general (NTL), electricity theft constitutes the bulk of NTL (Depuru et al., 2011)

Four main adverse impacts can be identified (Lewis, 2015). Primarily this would increase electricity prices as the utility would have to cover both the economic loss generated by the electricity theft and the additional cost of network maintenance. In the second place, the quality of the power supply could worsen due to the risk of overloading the system. Overloading of the system often triggers interruption of power supply, which results in loss of power output and risk of damaging appliances (Lewis, 2015). Additionally, the impact of power outages on firms is immense. Cole et al. (2018), found out that if a firm could lower its average level of power outages to 118 hours a year, this would increase their sales by 85% at least (Cole et al., 2018).

Thirdly, NTL has an impact on the amount of funding utilities can invest in the maintenance and renewal of the network. Fourthly, electricity theft is prone to generate other hazards (Lewis, 2015). The case of the town of Lubumbashi in DRC illustrates that perfectly[7]. During the month of September 2023, someone tried to steal electricity from SNEL's installations, this led to two electric towers falling and to an interruption of potable water supply, we can suppose that the tower was connected to some critical installations for water treatment or sanitation, or simply close to it. Several authors underlined the magnitude of this phenomenon and its harmful consequences on utilities finances in SSA (Wabukala et al., 2023). The impact on finance is even higher for companies such as SNEL that have low-enforced tariffs, which implies that they cannot adapt to the costs they are facing.

2.2 Previous studies on existing energy community

As mentioned in the Introduction, the concept of energy community (EC) is gaining further traction in the global north. Indeed, this concept has been explored from multiple points of view: social acceptance and network analysis (Standal et al., 2023); energy generation (Tomc & Vassallo, 2016); and the benefits of electricity trading (Heinisch et al., 2019). Many other papers on the topics mentioned above and others related to ECs are fully accessible (Barabino et al., 2023). In contrast, the granularity of data available and the amount of paper relating experiences and case studies of ECs in SSA is infinitely lower.

*2.2.1 Energy communities in the context of Sub-Saharan Afric*a

Many authors argue that ECs could have important benefits, especially concerning, energy justice, social capital development, empowerment, and energy democracy (Ambole et al., 2021). In fact, ECs in SSA essentially serve the purpose of seeing through electricity access and other basic needs that could be

[7] https://www.politico.cd/encontinu/2023/09/12/lubumbashi-plusieurs-quartiers-prives-deau-et-delectricite-apres-tentative-de-vol-des-cables-ayant-ecroule-2-pylones.html/140718/

improved by the introduction of electricity (health, poverty reduction, education, and water availability, among others) (Edomah, 2022).

Nevertheless, research on energy communities in SSA is limited and focuses mainly on stakeholder engagement rather than social acceptance, engagement, empowerment, energy democracy, or any other positive externality that might be linked to the implementation of ECs(Ambole et al., 2021).

Stakeholder engagement is central to the successful implementation of an energy community. Edomah (2022) illustrated that without the intervention of the Methodist church, the Yebu community would have not been provided with electricity. The methodist church allowed for establishing the link between the Yebu community and REA (Rural Electrification Agency) (Edomah, 2022).

Stakeholder engagement is therefore a necessary but not sufficient condition. Stakeholders' engagement alone would result in a top-down approach. This kind of approach has already been illustrated to be inefficient, especially in countries affected by structural inequalities (Ambole et al., 2021). Stakeholders have shown a significant interest in ECs in SSA (Ogunleye et al., 2022). Ogunleye et al. (2022), conducted a survey which demonstrated that 58% of the interviewed stakeholders were supportive concerning energy communities. It is therefore fundamental to adopt a participatory method and involve local people and future inhabitants in the decision-making process, allowing them to co-design the community would increase people's engagement in community activities, ensure the optimal functioning of the community, and increase well-being in general by providing electricity access (Ambole et al., 2021).

Ambole (2021) also identifies barriers to the successful implementation of ECs in SSA. Poor community engagement is without any doubt the main hindrance to the implementation of energy communities. The other two barriers stem from economic factors. Firstly, ECs in SSA suffer from a considerable lack of support in policies, which contributes to explaining the higher number of successes in terms of implementation from the global North, compared to the global South.

Secondly, solar installations imply a considerable upfront cost. This latter is often not affordable for people living in targeted areas (Ambole et al., 2021)

Finally, Ambole (2021) draws attention to the fact that several papers studying rural electrification in SSA through solar PV focus on a fairly limited scale, which prevents them from addressing the question of electricity access correctly (Ambole et al., 2021). This last aspect again highlights focusing economic impacts of different socio-technical systems (in our case energy communities) for electricity production, distribution, and consumption, and considers selected methods to numerically identify the target population. The approach will be explained in further detail in section 3, methodology.

2.3 Techno-economic analyses of off-grid communities in Sub-Saharan Africa

Based on a literature review, two common elements can be identified in the majority of the techno-economic analyses (TEA) in SSA. Firstly, they focus on a rather small sample, when the number of people living in the communities is specified. Secondly, the majority of TEA would ignore Central Africa and rather focus on South Africa (which has been excluded by our research) or Nigeria.

Dufo-López et al. (2012) undertook a TEA for a low-demand cooking device. While showing valuable results both from the economic and the environmental perspective, questions about the pertinence of the sample rise spontaneously. The study focuses on some of the countries with the lowest electricity access in the world. Nigeria counted more than 80 million people without electricity access at the time of the publication of the paper, and 86 million today (IEA, IRENA, WHO, UNSD, World Bank, 2023). In this perspective, the pertinence of a similar study for 50 people is questionable.

The same consideration could be addressed to Akinyele & Rayudu (2016), albeit their paper is extremely rich in terms of information, the community they are studying is composed of 24 households. Despite this number being low, compared to the people without energy access in Nigeria the paper demonstrated that solar PV is more efficient and cheaper than diesel in Bununu, Nigeria. Furthermore, they illustrated that it is possible to provide energy to an isolated community at a relatively limited expense, even considering load growth. Eventually leading to a reduction in CO_2 emissions (Akinyele & Rayudu, 2016). The only study we could review which had been effectuated on a rather large sample is the one by Samu et al. (2016) which focused on the city of Gwanda, Zambia. Showing that a hybrid system could provide energy with a very low LCOE even to a high number of citizens (26000 inhabitants). While not asserting that TEAs are not beneficial for small, isolated communities, there is a considerable amount of households in rural areas that are too distant from the grid to be considered for a potential grid extension. Nonetheless, they may still claim a significant per capita density and non-negligible photovoltaic potential. These households are typically underrepresented in the literature on rural electrification for SSA.

Another line of thought in TEAs in SSA is to effectuate simulations of consumption and production in order to encompass data scarcity. The most popular software to this effect is HOMER, this software also allows to undertake cost-optimization. This is the case of (Babatunde et al., 2017). They designed a hybrid system in Abedem, Nigeria. The system is composed of solar PV, a Wind turbine, and a diesel generator. The simulation is considerably sensitive to inputs provided during the demand estimation phase. The load was modelled after the indications provided by El Bassam et. al.(2004), we can imagine that people's needs changed nowadays. However, this is the only paper, jointly with (Eko & Paul, 2021) that provided not only the load but also the time of utilization for every appliance. Furthermore, the obtained result can be considered reliable if compared to similar literature (Babatunde et al., 2017) and to the results obtained in our simulations on DRC. The simulations assumed a population of 40 households (Babatunde et al., 2017).

Rice et al. (2023) focused on DRC, more precisely on the town of Lubumbashi, they also simulated the production with HOMER but consumption was not considered, the paper focused solely on the production of a hybrid system PV/diesel/battery and concluded that the produced load would be enough to satisfy the "local needs"(Rice et al., 2023). Nevertheless, their result showed that in this hybrid configuration diesel could never be used throughout the year and that a "PV/battery" configuration would present a slightly lower levelized cost of energy (LCOE). 0.08 $/kW compared to 0.1 $/kW for a PV/Diesel/Hybrid (Rice et al., 2023)

To recapitulate, we dispose of a limited body of literature on TEAs in SSA. However, excluding South Africa would diminish even further the already scarce body of literature available. The vast majority of scholars would focus on Nigeria. Literature on other countries can be found, yet it is more limited. The totality of the literature on TEAs in SSA focuses solely on techno-economic aspects. While part of the literature mentions increased socio-economic benefits as one of the reasons that justify the installation of solar PV, scholars tend to neglect the aspects and questions such as social acceptance of technologies, people's conception of electricity, and the hypothetical benefits of ECs in terms of empowerment, are ignored. The only exception in this regard is Banza et al. (2020). They successfully allied a TEA with a social investigation providing extremely valuable information on social drivers to acceptance of connections to mini-grids. The research showed that households with lower incomes are more likely to comply with a diesel-fueled MG or to find a "collective solution"(Banza et al., 2020).
When analysing economic inputs in the context of sub-Saharan Africa, the seminal work by IRENA (IRENA, 2016) serves as the foundational reference. Despite not being the most recent report, it stands as the most authoritative and current source accessible for this specific category of data. The reliability of the information contained therein establishes it as the primary reference point for the analysis at hand.

2.3.1 Demand estimation in the context of data scarcity

Various models and frameworks have been devised to address the challenge of estimating demand in situations characterized by limited data availability. One noteworthy example is the Remote-Areas Multi-energy systems load Profiles (RAMP), as presented by Lombardi et al. (2019). This model, available as open-source software, facilitates the generation of stochastic load profiles. While our approach shares similarities with RAMP, it is essential to note that RAMP is more intricate, designed specifically to compute energy profiles for both residential and commercial users(Lombardi et al., 2019).

RAMP introduces a level of complexity by accommodating factors such as random switch-on time, switch-on event duration, and duty cycles. This heightened granularity enables the creation of accurate load profiles. However, it is imperative to acknowledge that modelling for a community exceeding 2900 households becomes a time-intensive process, necessitating the individualized modelling of each household. This would result in the necessity for further computation before modelling, since when accounting for ownership in a community we need to know the percentage of households that have to be built with a certain number of appliances. Despite this time investment, our efforts yielded comparable results to those obtained with RAMP, thereby validating the robustness of our methodology.

ESMAP (Energy Sector Management Assistance Program) developed its own approach to categorize electricity demand, the multitier framework (MTF)(ESMAP, 2015). This approach was developed by the World Bank. It is characterized by five tiers of consumption, with each tier corresponding to a specific level of electrical consumption. The five tiers are described as follows:

Tier	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Minimal annual consumption (in kWh)	4.5	73	365	1250	3000

Table 2 Multi-tier framework's consumption categorization (ESMAP, 2017)

Further details are provided by the authors, and the typical appliances that a household would own according to the consumption tier are enumerated as follows:

Tier	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Appliances	N.A.	Lighting and phone charging	Lighting, phone charging, television and fan	Tier 2 and any medium-power appliances	Tier 3 and any high-power appliances	Tier 2 and any very high-power appliances

Table 3 Appliances and their relative tier according to the MTF (ESMAP, 2015)

The MTF present a strong homogeneity which is inherent to the purpose it serves, that is to say, measure electricity access across different countries. The MTF is meant to be a sort of common approach for all the countries, their specificities are therefore neglected. Sub-Saharan Africa is highly heterogeneous, therefore this approach, while being a reference in international organizations tackling the matter of electricity access, would not allow it to satisfy the aims of this paper.

2.4 CO_2 reduction and life cycle assessment in Africa

LCA analysis is the solid method in literature when it comes to CO_2 analysis (Karkour et al., 2021) provided a state of the art of LCA analysis in the African continent. The literature about Africa in this field is highly limited Karkour et al. (2021) could find 199 papers on the topic for the whole continent. Approximately the same amount of paper was found in Thailand.

All countries are not equally represented, the pattern we observed for the other field is reiterated, the most represented countries are: South Africa, Tunisia and Egypt, these three countries alone account for almost 50% of the paper reviewed (Karkour et al., 2021).

SSA is therefore underrepresented, once again, which is particularly flagrant in Central Africa.

More specifically, no paper was found on DRC, Despite the central role the country is destined to play (more than 200,000 million inhabitants are foreseen in 2050), scholars are ignoring this country (Karkour et al., 2021).

3. Data and methods

This section illustrates the methodology of analysis utilized in this research. The aim of this section is to thoroughly delineate the methodology and approach employed throughout this study. This section constitutes one of the central parts of this work, the purpose hence is to provide a comprehensive and detailed presentation, and simultaneously, to point out the limits of this work.

3.1 Input Data

The model for the techno-economic analysis is developed based on diverse datasets. As the purpose of the thesis is to address data scarcity, all the data and the datasets used throughout the study are accessible via the Internet. These are the main datasets utilized:

Electoral data from DRC. This data provided a list of people registered in electoral lists, as well as a list of electoral districts divided into rural and urban communities. This dataset provided us with approximately the number of inhabitants.

MICS (Multiple Indicator Cluster Surveys) by UNICEF. This survey by UNICEF has the purpose of gathering data on well-being. The survey has a section related to living conditions in which they provide data on how many people dispose of the selected appliances, along with many other different data that we did not consider as they are not relevant to the scope of this study.

PVGIS (Photovoltaic Geographical Information System) Radiation dataset. This dataset developed by the European Commission's Joint Research Centre (JRC) provides solar energy and photovoltaic (PV) data for various locations. Data on solar irradiation are provided by this dataset.

UN-HABITAT data. UN-HABITAT provided data on the average number of people living in a household for every country in SSA, this data allowed for estimating the number of households in rural communities, starting from the number of voters.

*RENEWABLE NINJA***.** This is an open web platform that allows to simulation of the power output of wind and solar power plants located anywhere in the world.

An overview of the input data is presented in Table 4:

DATASET	*DESCRIPTION: INFORMATION IN THE DATASET*	*OBJECTIVE*
ELECTORAL LIST OF DRC	N° of people registered in the electoral lists, List of rural and urban communities	Approximate the population residing within rural communities of DRC.
MICS (Multiple Indicator Cluster Surveys) by UNICEF	Most diffused appliances per household and ownership	ascertain the prevalence of household appliances in the nation, while determining the corresponding ownership figures among the populace.
PVGIS Radiation dataset	Solar irradiation data	Provide solar irradiation data to calculate the energy output of the PV System
UN HABITAT	Average people living in the same household per country	Identify the average number of occupants per residence and subsequently formulate an estimation of the overall demand
RENEWABLE NINJA	Data on out solar PV production	Calculate the output of solar panels

Table 4 Overview of input data (elaborated by the author)

3.2 Methods

This section illustrates the research's analytical methodology and expounds on the calculations conducted throughout the study. It includes an introduction a graphic overview of the methods, and the calculation related to the energy communities' typologies in SSA. The method utilized to estimate energy demand and load profile. The method used to size the PV system. The input data for the cost of technologies; main equations for techno-economic analysis, CO_2 reduction potential, and limitations.

3.2.1 Overview of the methods

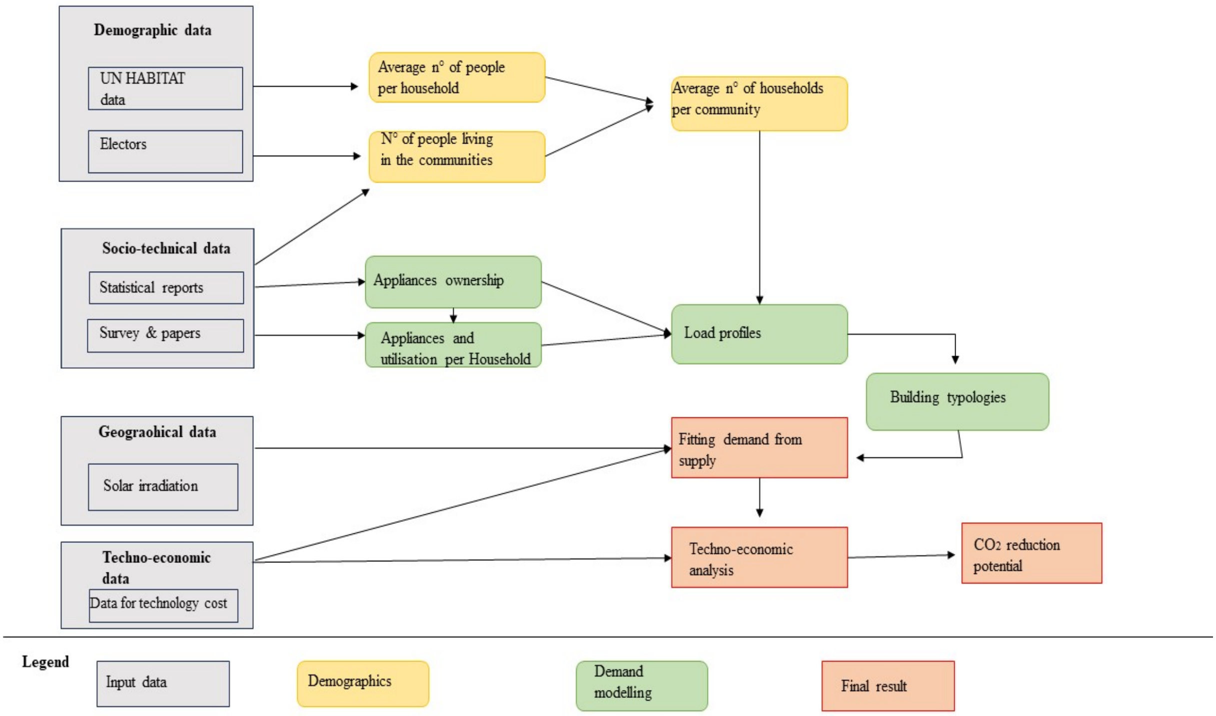


Figure 7 Graphic overview of methods (elaborated by the author)

3.2.2 Defining the rural context

Solar could play a central role in this perspective in both urban and rural contexts in SSA. If there is a consensus about the utilisation of microgrids in rural contexts, where the grid is not present; the same cannot apply to urban ones. However, defining what is an urban context and what is a rural context in SSA is not that straightforward. Various zones in SSA are neither rural nor urban. They are a sort of in-between that some authors call peri-urban, and others call urbanizing zones. Many scholars in geography focused on characterizing these zones (Halleux, 2015; Guillou & Girard, 2023). This nuance is not considered in the administrative categories of most countries in SSA which still rely on the urban-rural dichotomy, despite this latter being inadequate to describe the realities in SSA.

This lack of precision in describing the heterogeneity of realities in SSA contributes to the failure of energy policies in the sub-continent.

For instance, Guillou & Girard (2023) conducted an investigation focusing on mini-grid installations in semi-urban regions with rural classification, located within a 50 km radius of the town of Kaolack, Senegal, which houses approximately 1,229,000 residents. Among the inhabitants in this vicinity, ranging from 10,000 to 20,000 individuals are connected to the conventional grid. To facilitate the deployment of mini-grids, the rural electrification agency employs four specific criteria, encompassing administrative aspects (rural areas), morphological considerations (high population density), geographical factors (minimum distance of 5 km from the grid), and socioeconomic dimensions (high demand, economic activities). The demographic profile of all localities under scrutiny featured a population size ranging from 700 to 2,000 inhabitants.

Urbanizing localities exhibit a growing prevalence of energy-intensive activities coupled with inadequate or markedly unreliable network utilities, thus presenting an opportune scenario for the implementation of mini-grids by private entities. This situation arises due to the presence of unmet demand that exceeds the capacity of the conventional grid. Guillou contends that in the context of urbanization, the exploration of mini-grid deployment merits further scrutiny, and it is imperative to reevaluate the commercial framework to mitigate the potential perpetuation of inequalities that may arise from private electricity management (Guillou & Girard, 2023).

Another important piece of precision it's that when we refer to "rural communities" we intend to indicate the administrative sense of the term. We essentially want to describe a territorial entity whose predominant way of living is mainly rural.

Defining what is rural might be complex, as it is likely to change according to the context (Guillou & Girard, 2023). For the scope of our study, we will define rural communities that are isolated from the grid and whose population density is relatively low. A list of rural communities is already provided in the electoral list and another one is present in the statistical report. The identification of rural communities is therefore based solely on the administrative indications provided by DRC through the electoral list and the statistical report.

3.2.3 Calculation of energy community typologies in SSA

DRC lacks a current general population census, with the only available one dating back to 1984, conducted by Institut des Statistiques. However, this outdated census cannot be considered reliable at present.

Given the absence of a recent general population census, we resorted to using electoral lists to estimate the population in each rural community. Yet, this approach comes with significant limitations. One major constraint is that at least 50% of the population consists of underage individuals, making it impossible to account for them in the electoral lists, as the legal voting age is 18 in DRC. Additionally, the fact that some rural communities could have been aggregated for electoral purposes further adds to the method's drawbacks. Furthermore, some people could not be registered on electoral lists. Also, electoral lists do not provide data on the geographical distance between communities and people density per km. To reduce this bias to the minimum we took the electoral list for municipalities. The latter, constituting one of the lowest points of the administrative hierarchy, often exhibit a pronounced inclination to maintain proximity with their respective communities.

Before diving into the methodology in further detail it is fundamental to provide a clear explanation of the administrative hierarchy of DRC.

The organizational framework of administrative hierarchy in the Democratic Republic of Congo serves the purpose of subdividing its expansive territory into smaller administrative units, thereby facilitating enhanced governance and oversight. This hierarchical structure comprises several tiers, commencing with the highest level at the national tier. Subsequent to this, the hierarchy encompasses "provinces", each composed of "villes" (towns) and" territoires" (territories). These "territoires," in turn, undergo further division into "communes rurales" (rural communities), "secteurs" and "chefferies". Notably, the latter two tiers introduce an additional layer of complexity represented by "groupements", as illustrated in Figure 6.

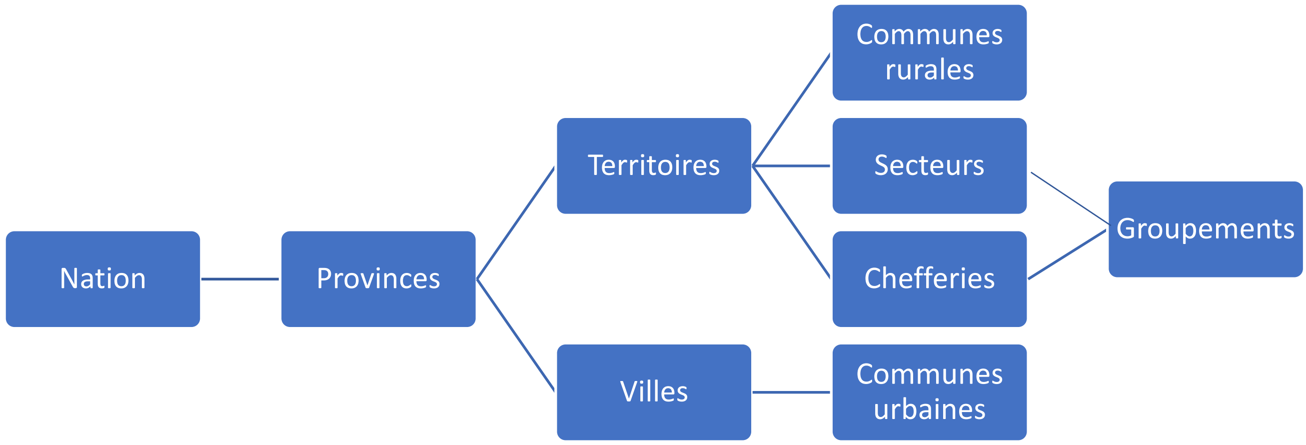


Figure 8 Administrative hierarchy of DRC based upon the organic law 08/016 of 7 October 2008 (elaborated by the author)

Our research rationale led us to select the second-highest administrative tier in this hierarchy, primarily focusing on "communautés rurales" (hereafter referred to as rural communities). This choice was deliberate, as the alternative consideration of "chefferies" would have entailed working with larger numerical quantities, consequently intensifying the level of uncertainty inherent in our study.

Despite these considerable limitations, the electoral list method still offers rudimentary insights into the population count within each rural community. Such basic information is crucial for demand estimation purposes.

We proceeded to calculate basic descriptive statistics indicators of the distribution; the results will be presented in the table below.

Mean (μ)	Standard deviation	Kurtosis
18 403	13877,81443	2,77446122
Variance	Median (M)	Skewness
192593733	15 439	1,50503969

Table 5 Descriptive statistics of voters (elaborated by the author)

Given that we are dealing with a substantial distribution, we opted to utilize the Median (M) rather than the mean (μ), as the latter is more susceptible to the influence of extreme values. Accordingly, Median should signify the central value within the distribution. Specifically, in our case study, M corresponds to the middle value in the distribution, representing the number of voters in rural communities, which shows the central tendency of the sample analysed therefore a better representation of the number of people in a rural community in DRC especially with high skewed populations. Thus, we can posit that this figure denotes the average number of people residing in a rural community. In reality, the drivers that push people to live in a certain context cannot be determined mathematically, that is why we might have communities of 50 people and communities of 50,000.

The calculation for both the mean (μ) and median (M) is detailed below. It is crucial to acknowledge that this information is highly likely to be an approximation, given the absence of available data. In such circumstances, the only viable alternative would be to resort to an arbitrary selection. Nonetheless, in real-world scenarios, when installing a PV system, we would inevitably be compelled to liaise with local authorities at some point, thereby potentially obtaining data on the population. Though this data might not be entirely current, it would nonetheless provide a general overview.

Determining the total number of individuals residing in a community allows us to calculate the average number of households in the same community (Hc). To achieve this, we divide M by the average number of individuals per household (H), which is 5.3 in DRC, as reported by MICS and DHS. While we might assume that this value could be slightly higher in rural settings (Adhikari et al., 2023; Akinyemi et al., 2014), our existing data does not possess this level of granularity.

However, it would be reasonable to infer that, given the release of the MICS in 2018, both rural and urban averages experienced a decrease, with the rural average converging towards the overall average observed in 2018.

The aforementioned calculations are encapsulated by the subsequent equations:

Equation 1 Average number of households in rural communities in DRC

$$\boldsymbol{H_c = \frac{M}{H}}$$

Equation 2 Median (M)

$$if\ odd,\ M = \left(\frac{n+1}{2}\right) orderedvalue$$

$$if\ even,\ M = \mu\ (\frac{N}{2} + \frac{N}{2} + 1)\ ordered\ values$$

N be the total number of observations (people registered on electoral lists)

Equation 3 Mean (μ)

$$\mu = \frac{1}{N} \sum_{i=1}^{N} x_i$$

The distribution being vast, we decided to calculate percentiles to obtain data that are easier to manipulate and more representative of reality. H_c is 2912.92 (2913), calculating percentiles out of this distribution allows for creating different consumption typologies that will be discussed later. Consumption typologies essentially consist of five consumption tiers.

In the forthcoming section, we will delve into the calculation related to energy demand.

3.2.4 Calculation of energy demand profiles

Since we could not find any reliable data on energy demand in DRC, we proceeded to calculate the input data ourselves. In the first place, several papers about behavioural patterns of energy consumption in SSA, the main one being (Eko & Paul, 2021), papers on South Africa were excluded.

Appliance	Power (W)	Ownership	Utilisation	N° of hours
Fridge	180	23,6	00:00 - 23:59	24
TV	140	64,4	17:00 - 22:00	5
Fan	60	28,3	18:00 - 5:00/12:00 - 15:00	14
Lights	8,5	1	18:00 - 22:00/ 6:00 - 7:00	5
Radio	1,3	31,3	6:00 - 8:00/ 13:00 - 15:00	4
Cell phone	20	1	18:00 - 19:00	1
Stove	1500	27,2	12:00-13:00/19:00-20:00	2
AC	1200	2,6	12:00-17:00	5

Table 6 Input data used to model demand estimations (Eko et al. (2021), Radhika Khosla et al (2021), Yilmaz et al. (2020), Babatunde (2017))

This paper provided data on average hours of utilization for basic appliances in Malawi. We suppose that we can extend those data to DRC because according to GIZ the utilisation of basic appliances can be standardized (GIZ, 2016). Also, according to (Wu et al., 2015), the top three peak hours are very similar for DRC and Malawi, (respectively:19, 20, 21 and 18, 19, 20), which denotes a similar energy use. Furthermore, the per capita GDP of the countries are similar, therefore we can exclude an economic driver which could lead to higher or lower energy consumption.

After acquiring the utilization hours, we proceeded to compute the energy consumption (in kilowatt-hours, kWh) for each appliance, based on a list of fundamental appliances gathered from various scholarly works. By aggregating these distinct loads, we derived a daily load profile per household. The pertinent steps are summarized by the following equations:

Where:

τ is the operating time of the appliance,

π represents the power rating of the appliance,

θ symbolizes the percentage of people who own those appliances (ownership) in DRC. Ownership data were obtained by the MICS survey.

Equation 4 Calculation of one hour load for a single appliance (π_h) in W

$$\pi_h = \pi \times \theta$$

Equation 5 Calculation of one hour load for all the appliances (π_τ) in W

$$\pi_\tau = \sum_{i=1}^{n} \pi_{hi}$$

Equation 6 Calculations for daily load profile

$$\lambda = \sum_{i=1}^{24} \pi_{\tau i}$$

Equation 7 Load profile in kWh

$$\lambda_{kwh} = \frac{\lambda}{1000}$$

For the annual load profile per household, we will multiply λ_{kwh} by 365,

$$\lambda_{kwh/y} = \lambda_{kwh \cdot 365}$$

while for the community load profile, we have to multiply it by H_c (2913).

Different energy demand profiles will be built to simulate households with diverse consumption typologies. This will allow for considering different typologies of consumption, as mentioned in the precedent section (Typology 1 [T1], Typology 2 [T2], and Typology 3 [T3]).

Having demonstrated the methodology for calculating fundamental energy consumption in the Democratic Republic of the Congo (DRC), the subsequent discussion will outline the process of generating alternative typologies using the methodology described above.

Based on the presented tabular data, it is evident that the Typology 1 consumption model (Table 8) aligns with the tier 2 categorization of the MTF(Table 2). A potential point of contention arises from the inclusion of a refrigerator in our model, as the Multi-tier Framework (MTF) holds a broader scope (Southeast Asia and Sub-Saharan Africa) compared to our basic typology (T1), which relies on survey-derived data concerning appliance ownership within the DRC. The consideration of ownership percentages further bolsters the accuracy of our model over the MTF.

Utilizing this foundational framework as a springboard, it becomes plausible to propose the construction of four additional tiers of consumption, applying the same methodology, namely, using equations 5, 6, 7, and 8. The initial three tiers will serve as active instruments for modelling energy consumption, while the latter two tiers are posited for future consumption modelling and scenario development.

Given the statistical fact that a mere 23% of the Congolese population possesses a refrigerator, the logical extrapolation is to design at least a consumption typology that excludes this appliance. Such a typology essentially reflects a consumption pattern that partially fulfills fundamental needs. In this contextual setting, our modelling endeavours will exclusively focus on lighting and phone charging, as inspired by the scientific literature (ESMAP, 2015 & Babatunde, 2017) and ownership data extracted from the Multiple Indicator Cluster Surveys (MICS). Notably, radio ownership will not be considered in this typology due to the mere 31% population ownership figure as reported by UNICEF.

In comparison to the MTF, where the presence of a washing machine is contemplated under Tier 3, the outcomes of our analyses suggest that it would be more pertinent to the reality of the DRC not to include it in Typology 3. Specifically, only 4% of the population in the DRC possesses a washing machine. In contrast, statistical records indicate that 49% of the population owns an iron, while 27.2% own a cooking stove; the energy source for the stove is not explicitly documented and could encompass both gas and electric options.

In our modelling approach, we assumed that the stove operates on electricity. This assumption stems from the energy landscape in the DRC, where approximately 97% of the population relies on solid biomass like charcoal and fuelwood for energy (IEA, 2019).

We decided to assume that the stove is electric because nowadays 97% of the Congolese population uses charcoal or other solid biomass (fuelwood)(*IEA, 2019*). It is reasonable to suppose that there may be hindrances to gas distribution, otherwise, its adoption would be higher. This condition leads us to infer that gas distribution faces impediments, rendering the distribution bias negligible. Additionally, the scarcity of domestic gas availability in the DRC[8], coupled with its waning accessibility, lends support to our decision to classify the stove as an electric load for the purpose of modelling current and future demand.

For the sake of clarity, Table 4 compiles a summary of distinct appliances along with their corresponding ownership percentages, utilizing available data. Also, Table 5 delineates the various consumption typologies, detailing their composition (in terms of appliances) and associated daily demand per household in kilowatt-hours (kWh).

Appliance	Ownership (in %)
Radio	31.3
Television	64.4
Refrigerator	23.3
Electric stove	27.2
Washing machine	4
Iron	49.6
Fan	28.3
AC	2.6
Microwave	3

Table 7 Appliances present in the MICS survey and their ownership. Source : MICS

Typologies 4 & 5 represent a very intensive electricity utilisation, due to the presence of high-wattage appliances, the only difference between the two is that in Typology 5 we assume a higher degree of appliance adoption. This would allow for considering other scenarios of electrification at a national or community level. This work will solely focus on the latter. The scenarios will be described in further detail in section 3.2.7.

Typology 1	*Typology 2*	*Typology 3*	*Typology 4*	*Typology 5*	*Daily demand in kWh*
Lighting	Lighting	Lightning	Lightning	Lightning	
Charging (cell phone)	Charging (cell phone)	Charging (cell phone)	Charging (cell phone)	Charging (cell phone)	Typology 1 = 0.14
	TV	TV	TV	TV	Typology 2 = 1.90
	Radio	Radio	Radio	Radio	Typology 3 = 2.71
	Refrigerator	Refrigerator	Refrigerator	Refrigerator	
	Fan	Fan	Fan	Fan	
		Electric stove	Electric stove	Electric stove	
			AC	AC	
			Microwave	Microwave	
			Laptop	Laptop	
			Washing machine	Washing machine	

Table 8 Typologies of consumption according to end-uses (elaborated by the author)

[8] (2022, March 16). Kinshasa: le gaz à usage domestique se fait rare aux points de vente. Zoom Eco. https://zoom-eco.net/a-la-une/kinshasa-le-gaz-a-usage-domestique-se-fait-rare-aux-points-de-vente/#:~:text=Le%20gaz%20%C3%A0%20usage%20domestique%20se%20fait%20de%20plus%20en,procurer%20faute%20de%20stock%20disponible.

3.2.5 Fitting of PV supply from demand data

The system is configured as follows: Solar PV + Converter + Inverter + Batteries.

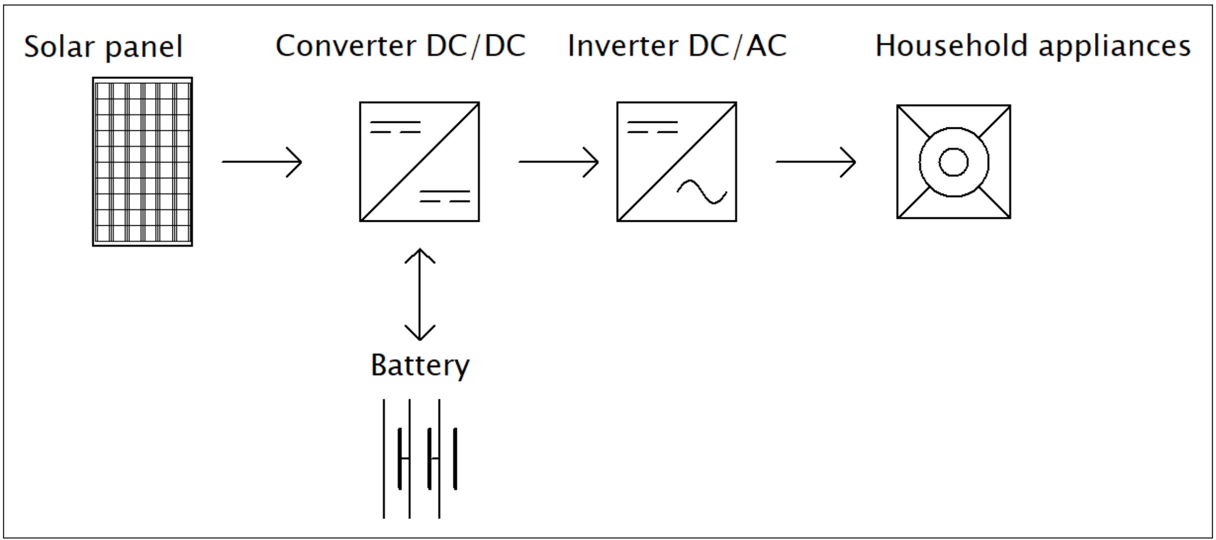


Figure 9 Graphic representation of the PV system (elaborated by the author)

The sizing will be done according to the "worst month" method. The distinguishing feature of this method lies in selecting the most adverse month, which corresponds to the period encompassing the highest aggregate surface area of PV modules (Anoune et al., 2018).

Contemporarily, the spectrum of techniques available to design PV systems is highly diverse, ranging from methods relying on the utilisation of artificial intelligence to others hinging upon mathematical modelling (Makhloufi, 2015).

These techniques can provide high-quality and extremely precise results, however, to yield reliable results they require extremely precise data, both on meteorological elements and on characteristics of photovoltaic system components.

The worst-month method (WM method) requires a lower amount of data. Moreover, due to its simplicity, compared to other techniques, it is perfectly adequate for situations of data scarcity, allowing it to overcome the limits aforementioned (Makhloufi, 2015).

Makhloufi (2015) conducted a comparative analysis of diverse methodologies and posited that, although the WM technique is characterized by its simplicity, it is proficient in yielding dependable outcomes pertinent to photovoltaic production. Nevertheless, an issue arises concerning the duration of battery autonomy, as the WM approach exhibits limitations in accurately delineating battery autonomy, thus giving rise to a dichotomic choice: either extend the battery's autonomy duration, incurring elevated system costs or curtail the duration, thereby risking unfulfilled load (Makhloufi, 2015).

Therefore, this method aligns perfectly with the purpose of estimating energy demand in a context characterized by the lack of data.

We proceeded to calculate the Peak Power of PV generation using the equation provided by Makhloufi (2015) which is cited below:

Equation 8 Sizing peak power solar PV

$$Pp = \frac{E_d}{Kt \cdot \eta_{bat} \cdot I_{rd}}$$

Where Pp stands for Peak power, E_d is daily energy demand, *Kt* is the temperature correction coefficient, and its function is to account for the loss in efficiency experienced by every panel due to high temperature. In the paper, Makhloufi (2015) assumes that the value of *Kt* is 0.67 but we could imagine a lower value for the selected location in DRC, as the paper was based on Algeria; it is safe to assume that the worst day (the day with the lowest level of irradiation) in Algeria has a higher temperature than the worst day in Pweto, DRC.

I_{rd} is solar irradiation level on the worst day.

η_{bat} is the efficiency of the battery.

In the same paper, the author also provides a formula to determine the battery's nominal capacity. The formula is explicated as follows:

Equation 9 Sizing of the battery

$$CN = \frac{E_d \cdot D}{\eta_{inv} \cdot DOD}$$

D represents the days of autonomy, DOD is the dept of discharge of the battery and η_{inv} is the efficiency of the inverter. *CN* is the battery's nominal capacity.

The number of days of autonomy was determined according to Orizu et al. (2019). Average solar irradiation was calculated for every day of the month, successively, the number of days in a row below that average was counted, resulting in 5 days. From December the 5th to December the 10th. The system being off-grid, one more day was considered in order to provide further security, eventually attaining 6 days of autonomy.

In the next section, we will outline the input data for the computations related to the cost of technologies.

3.2.6 Input data for the cost of technologies

Obtaining dependable data regarding capital expenditures (CAPEX) within the context of Sub-Saharan Africa (SSA) presents a formidable endeavour, particularly in the case of the Democratic Republic of Congo (DRC). Regrettably, a lack of available case studies relating to the DRC compelled us to resort to referencing CAPEX figures from projects situated in other nations. Nonetheless, in light of the various factors that can influence CAPEX, as outlined by ESMAP (2017), we propose three distinct CAPEX scenarios based on the specific attributes of the prospective project.

The main findings concerning the main features responsible for CAPEX formation, according to ESMAP (2017), are reported below but before reporting these latter it is fundamental to depict the composition of CAPEX.

CAPEX is composed of "hard costs", which consist of generation components (solar PV modules, inverter, and charge regulators), the storage system (batteries, cabling, and cells, monitoring and control system, powerhouse), conversion components (battery inverter and energy management system), distribution and consumption components when the grid is present; and costumer system components (end user indoor wiring and end-user appliances).

The other component of CAPEX is "soft cost", which consists of project development costs (management and engineering costs and capacity building and training of local operators) and logistic components (Storage of equipment, insurance, international shipping costs, local transportation costs) (ESMAP, 2017).

Part of the above-mentioned components are location-specific. In the study by ESMAP, direct correlations between the number of customers and the power output of the system could not be identified. It is therefore possible to infer that the number of customers will not influence the CAPEX (ESMAP, 2017).

Another factor playing a role in the CAPEX level is the project development costs. These latter tend to vary according to the project scale. If the project has been conceived as a single project, the price will be higher; but if the grid is part of a multi-grid program, then the price will be lower (ESMAP, 2017).

Whereas the costs pertaining to the equipment are relatively low, with distribution costs varying significantly according to the case. (ESMAP, 2017). OPEX only considers operational costs. The expenditures taken into consideration for OPEX will be discussed in detail in section 4.1.

Weekdays and weekends will be treated as equals. There are two reasons explaining this choice, Primarily, due to data scarcity, most of the time, real-time data on consumption during the weekend are not available; therefore it is consistent with the general practices observed in the literature to treat them as equal, yet acknowledging that they are extremely likely to differ (Dominguez et al., 2021). Furthermore, Adeoye et al. (2019) showed that in rural households in West Africa, the difference in consumption between weekdays and weekends is negligible. Postulation of the applicability of this pattern to DRC is made.

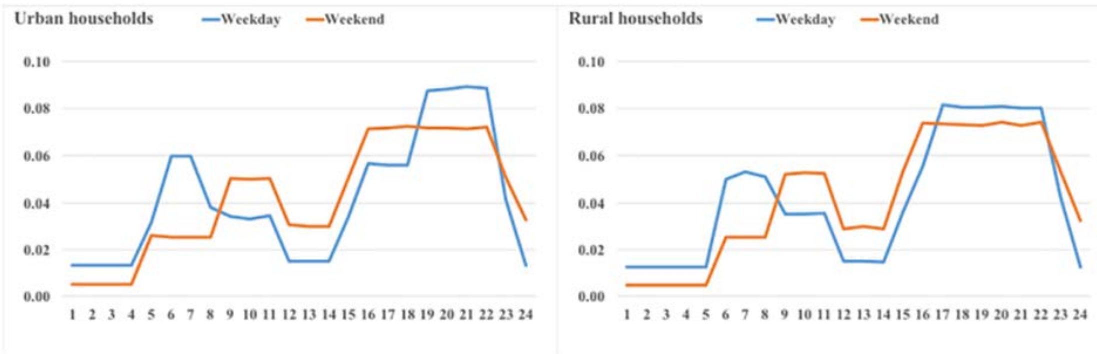


Fig. 5. Probability of use of cooking appliances in urban and rural households in Nigeria.

Figure 10 Comparison of weekdays and weekends with different appliances in rural West Africa (Adeoye & Spataru, 2019)

Both for cooking appliances and for audio-visual appliances the load would essentially remain the same. Nevertheless, we can observe a slight shift of the load curve during the weekend but the impact of this change on the total load is minor.

3.2.7 Techno-economic analysis

In this section, we will report the formulas used to calculate the following economic indicators:

Cash flows, net present value, payback period (PBP), LCOE, produced energy.

We will proceed to explicit the different formulas below:

Cash Flows (CF)

Equation 10 Cash flows

$$CF_n = Benefit_n - CAPEX_n - OPEX_n$$

Where n is the number of years

Payback period:

Equation 11 Payback Period

$$PBP = \frac{Initial\ investments}{Annual\ net\ cash\ flow}$$

LCOE

Equation 12 LCOE

$$LCOE = \frac{CAPEX + \sum_{n=1}^{Lifetime} \frac{OPEX_n}{(1 + CoC)^n}}{\sum_{n=1}^{Lifetime} \frac{Egenerated, n}{(1 + CoC)^n}}$$

In the formula usually found in literature r replaces the Cost of Capital (CoC), and r represents the interest rate. But for this specific case, CoC was chosen over interest rate. The reasoning behind this choice will be provided below.

Total energy produced:

Equation 13 Total energy produced.

$$E_{p=} Size * Cfactor * \eta\, inverter * 8760$$

A lifetime of 25 years will be assumed, as this is consistent with the literature. Cost of Capital (CoC) will be used instead of the interest rate. The definition of CoC is a question that originated several debates in literature. Scholars in economic theory discussed this matter deeply without reaching an exhaustive answer. (Modigliani & Miller, 1958). Nevertheless, several definitions are available. This work will build upon the definition provided by the Oxford Dictionary of Economics, which defines CoC as "*The rate of return an enterprise has to offer to induce investors to provide it with capital*"(John Black et al., 2009) CoC was chosen over interest rate as the latter can be impacted by different factors that are likely to enhance interest rates, such as the presence of default or risk premium (John Black et al., 2009) Pertaining to CoC, an extensive list of CoCs for African countries was provided by Egli et al. (2023).

The PV will be ground-mounted. Lithium batteries will be utilized as they are the most diffused alternative in the market at the moment.

3.2.7.1 Geographical data of the location (site characteristics)

The site of this study, the rural community of Pweto is located in the administrative territory of Pweto, in the province of Haut-Katanga, in DRC (8.4698° S, 28.9034° E). Solar irradiation data was obtained through the site of JRC.

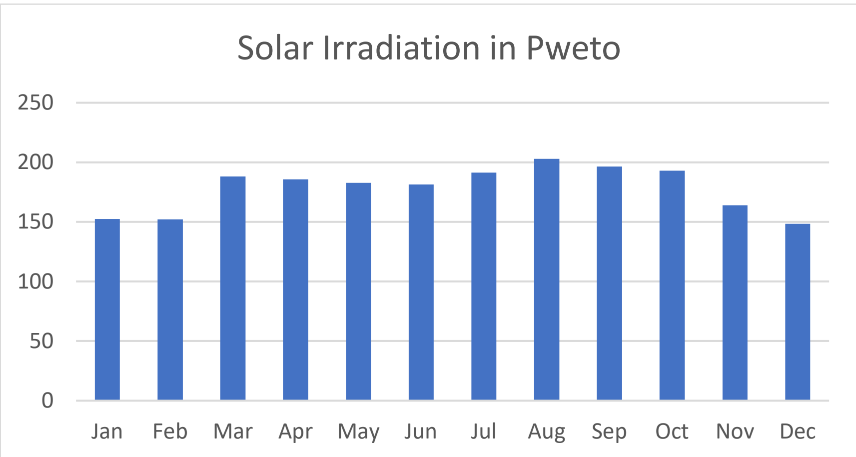


Figure 11 Solar irradiation in the town of Pweto in 2019. Data from PVGIS (JRC). (Chart elaborated by the author)

Pweto was the scene of intense clashes during the Second Congo War that ended in 2004, and nowadays, notwithstanding the efforts for reconstruction the town hosts mainly rural settlements (Scherrer, 2002).

We chose the town of Pweto because this town is characterized by an intense density of population which makes feasible the hypothesis of a rural context with approximately 2913 households, the whole "*territory*" of Pweto counts 30 307 inhabitants. This makes it reasonable to suppose that in the rural community of Pweto, there are at least 3000 inhabitants, since the territory of Pweto is composed of Pweto, Moero, Kilwa, Chefferie Kiona-Nzini, Chefferie Mwenge, Chefferie Mpweto.

Figure 12 Pweto (Licensed image, https://stock.adobe.com/fr/images/small-village-near-pweto-katanga-democratic-republic-of-congo/240073081)

Also, this town is provided with excellent solar irradiance, and consequently, a very interesting photovoltaic potential, resulting in a capacity factor of 17.8%.

Through the utilisation of Geographic Information System tools, we could measure the distance between Pweto and the nearest grid, which is 238 km. Far enough to consider Pweto as an isolated community (grid-wise). Connecting Pweto to the national grid would result in a cost of 4 million dollars approximately (4 760 000 $).

Knowing that the full budget of ANSER (*Agence nationale pour l'électrification rurale et périurbaine*) for the year 2022 was less than 5 million dollars (4,637,805.74$) (ARE, 2022), that cost would be probably too high for DRC's national budget. Furthermore, if we consider the fact that the area between the grid and Pweto consists mainly of vegetation, incurring a similar cost to extend the grid in order to reach a small number of people would not be cost-effective from the government's standpoint. In this perspective, solar mini-grids (MG) are the perfect solution, as they can provide electricity for various people for a cheap price and a relatively simple installation.

3.2.7.2 Scenarios

Three scenarios will be provided to analyse possible implications for the community if intervention is made. The factors on which policymakers can intervene are fairly limited, they resume to tax and subsidies, Cost of Capital, and combinations of the aforementioned.

3.2.7.2.1 Subsidy

The primary objective of the first scenario is to assess the implications of implementing subsidies. The designated criterion for evaluation is the attainment of an LCOE of 5 $cts/kWh, a figure slightly below the enforced average electricity tariff in the Democratic Republic of the Congo (DRC), which stands at 7 $cts/kWh. The formula adopted to calculate the subsidy will be the following:

Equation 14 Quantifying the subsidy.

$$\delta = LCOE - \Delta\%$$

δ represents the LCOE we want to obtain with the subsidy.

LCOE represents the actual LCOE.

$\Delta\%$ represents the percentage change between actual LCOE and wanted LCOE.

3.2.7.2.2 Reducing Cost of Capital

The second scenario will consist of considering a reduction of Cost of Capital (CoC), two different CoC will be considered. (Egli et al., 2023) provide a CoC for different countries in SSA. They consider two cases, the first one in which the funding is only coming from the private sector, and the second one in which they are coming from the public sector (government). For DRC, this would result in a CoC of 23.5% in the first case and 10.5% in the second. It is fair to assume that the second interest rate can be used for the case of DRC, as ANSER is financing more and more projects of rural electrification but both cases will be calculated. Eventually, a sensitivity analysis of CoC will be performed, in order to test its impact on the LCOE. The CoC will be tested for every value between 10 and 1.

3.2.7.2.3 Combining multiple measures

In this section, we will test a combination of the factors aforementioned, tax and grants will also be explored. The results of the sensitivity analysis will be combined with grants. As underlined in section 4.1, batteries and inverters are the most expensive components of CAPEX & OPEX. Since the government has the duty to grant people access to energy, as stated in article 48 of the constitution of DRC, a way to comply with this duty could be to finance batteries, and inverter (and their replacement). This option will be combined with a reduction in CoC.

3.2.8 CO_2 reduction potential

In this section, we will provide the methodology utilised to assess the CO_2 reduction potential of photovoltaic solar panels, compared to diesel generation. PV is linked to the utilisation of critical minerals necessary to produce solar cells. The mining of those minerals affects human health and has a significant impact on the countries in which minerals are collected (Hernandez et al., 2014). Tracking critical minerals' value and supply chain is extremely difficult. Nevertheless, several scholars are trying to provide frameworks for more "responsible" approaches (Tyagi et al., 2023; van den Brink et al., 2019). Although this topic is far from the scope of this work, it needs to be mentioned as it is a particularly concerning topic for DRC.

Computing the social cost of CO_2 emissions is an extremely hard task, quantifying the environmental costs of electricity generation implies considering a plethora of factors and externalities, as well as their interactions. We will therefore rely on a much simpler approach based on the social cost of carbon dioxide calculated by Rennert et al. (2022), which is 185$. This cost considers different kinds of damage to the environment (rising sea levels, increase in drought, CO_2 emitted by buildings, among others). According to the IPCC[9], the carbon price in the market does the same, albeit being much lower (Rennert et al., 2022) argue that the carbon price in the market is underestimated. Firstly, we will calculate the CO_2 emissions produced per kWh, secondly, we will look at the price of CO_2 permits in the market, to obtain an economic value for these elements.

[9] https://unfccc.int/about-us/regional-collaboration-centres/the-ciaca/about-carbon-pricing#How-does-carbon-pricing-work?-

To calculate the emissions of the diesel generator we will use a "conversion factor" (β) calculated by Jakhrani et al. (2012), which is 1.27kgCO_2/kWh. In other words, the diesel generator will emit 1.27 kg of CO_2 for every kWh of electricity produced. Of course, the number of kgs emitted will vary according to the efficiency of the generator.

Eventually, this factor will be multiplied by the average annual consumption of a household during a year ($\lambda_{kWh/y}$). The same procedure will be adopted for calculating the environmental cost of electricity generation of solar PV. This latter is a less carbon-intensive diesel generator, reason why the «conversion factor» will change. According to Pehl et al. (2017), the estimated conversion factor (α) is 6gCO_2/kWh. Accounting for emissions related to battery storage is pivotal (Frischknecht et al., 2020) provide data on CO_2 emissions related to a PV system with Li-ion batteries (Iron-phosphate-lithium), asserting that 20 kWh of storage capacity is equivalent to 88 g of CO_2 emissions. According to this data, the emissions related to the storage capacity (B) will be calculated and added to Equation 16

The equations to calculate the environmental cost of generating electricity for the two technologies are twofold:

Equation 15 Carbon dioxide emissions related to electricity generation by diesel generator (in kgCO_2eq)

$$\lambda_{kWh/y} \cdot \beta$$

Equation 16 Carbon dioxide emissions related to electricity generation by solar photovoltaic (in kgCO2eq)

$$\lambda_{kWh/y} \cdot \alpha + B$$

The results of both equations will be multiplied by 185$, resulting in the environmental cost for electricity generation of the two technologies. This cost will be provided for the three typologies computed.

4. Results

This section will focus on providing the results yielded by the methodology described above. Initially, an examination will be conducted on both capital expenditures (CAPEX) and operational expenditures (OPEX). Subsequently, attention will be directed towards the analysis of the levelized cost of electricity (LCOE) and cash flows. Thirdly, the investigation will transition to the various scenarios that have been modelled, culminating in the presentation of insights derived from the carbon dioxide (CO_2) analysis.

4.1 CAPEX & OPEX

It is of paramount importance to show the different components of CAPEX and OPEX. The two play a pivotal cost in the determination of the total costs of the system. Hard costs considered in the modelling of the CAPEX of the system were solar panels, batteries, inverters, and charge controllers. Whereas the soft costs encompass logistics, development and installation, and customs & VAT. While costs considered in the modelling of OPEX of the system are fixed operations & maintenance costs, the replacement of the inverter, and the replacement of batteries. Batteries and inverters constitute the highest cost for CAPEX & OPEX. The yielded CAPEX and OPEX are illustrated in Figure 13.

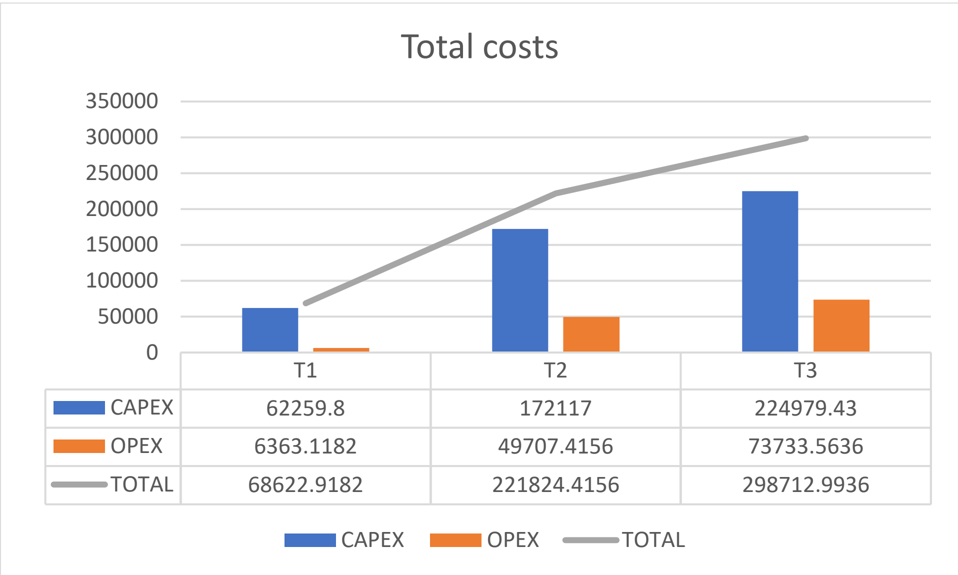


Figure 13 Total costs of the system for each typology (in dollars) (elaborated by the author)

Computations based on CAPEX & OPEX allow for the obtention of LCOE. LCOE plays a central role in the computation of the provided results. However, it is noteworthy that the Levelized Cost of Electricity (LCOE) analysis exclusively takes economic aspects into account and does not encompass the broader social benefits associated with electricity provision, as indicated by Moner-Girona et al. (2021). Moner-Girona et al. (2021) illustrate that photovoltaic (PV) systems have a favourable impact on job creation, improve access to quality education, and enhance healthcare services.

4.2 LCOE of Consumption typologies

Our analyses have resulted in the identification of three primary typologies. The initial category corresponds to minimal consumption, satisfying fundamental needs. The second typology encompasses a level of consumption that remains low overall but affords a decent standard of living, designated as T2. Finally, the third typology closely resembles the second, allowing for an even higher level of comfort, and shall be referred to as T3. Further elucidation on the construction of these typologies is provided in Section 3.

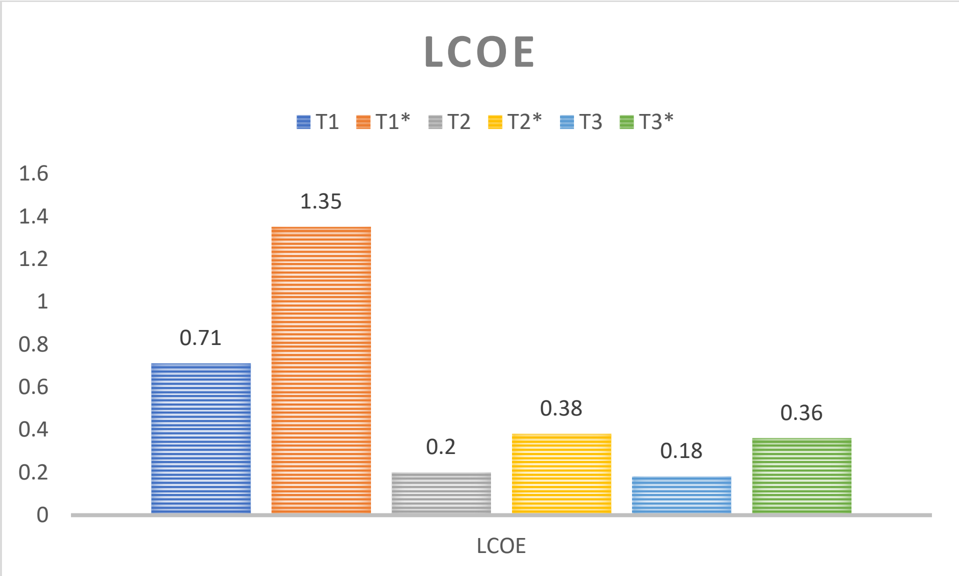


Figure 14 Graphic representation of the LCOE of each typology (elaborated by the author)

Before presenting the results, we will briefly plot the input in the table you can find below.

Typology	Lifetime	CoC	Inverter efficiency
T1	25 years	10.5%	98.95%
T1*	25 years	23.5%	98.95%
T2	25 years	10.5%	98.95%
T2*	25 years	23.5%	98.95%
T3	25 years	10.5%	98.95%
T3*	25 years	23.5%	98.95%

Table 9 Input variables for modelling of techno-economic parameters (elaborated by the author)
We shall denote this typology as T1 when the associated CoC (Cost of Consumption) is 23.5%. A «*» will be appended to the typology's name, rendering it as T1*. This nomenclature will also be extended to T2* and T3*.

The load curve of T1 is plotted below.

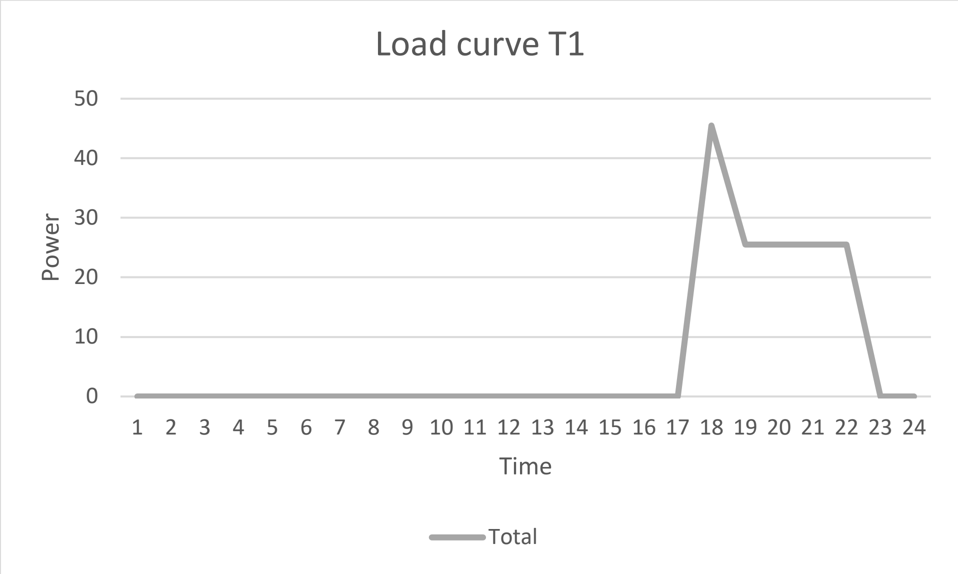
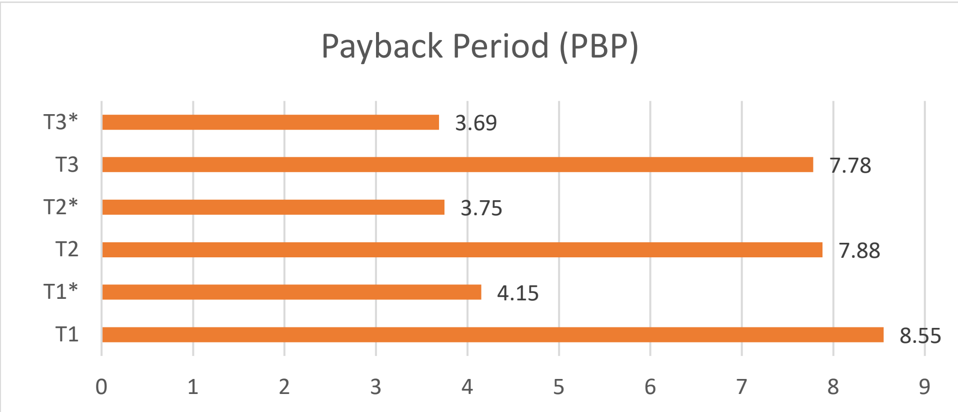


Figure 15 Load profile T1(elaborated by the author)

As we can observe in T1, the consumption is concentrated in the evening. The load is solely composed of lighting and phone charging, as explained in Table 8. This load curve corresponded to a daily consumption of 0.14 kWh per household. Which translates to a daily load of 429 kWh for the whole community. We sized the solar system accordingly, which resulted in a 9 kW solar system with a storage capacity of 3580,5 Wh. This solar plant in the designed location of Pweto would provide electricity with an LCOE of 0.71 $/kWh. The total expenditures correspond to 68622,92$ and they are divided into CAPEX 62259,8$ and OPEX 6363,118$, as illustrated in Figure 13.



	T1	T1*	T2	T2*	T3	T3*
PBP	8.55	4.15	7.88	3.75	7.78	3.69

Figure 16 Payback Period for each typology (elaborated by the author)

The payback period (PBP) is 8.55 years, the payback periods for the other typologies are displayed in Figure 16. The produced energy throughout the whole duration of the project is 117 599,38 kWh. Electricity produced during the whole lifetime of the project is shown in Figure 17. The computations assumed a 10.5% interest rate, according to the assumption of Egli et al. (2023). Egli et al. (2023) also assert that this cost of capital (CoC), refers to installation fully funded by the government, as they assume that MGs are solely funded by the private sector, which, according to their results, led to a CoC of 23.5%. In reality, for

DRC it is fair to assume that the government might contribute to funding MGs since this is already happening through ANSER.

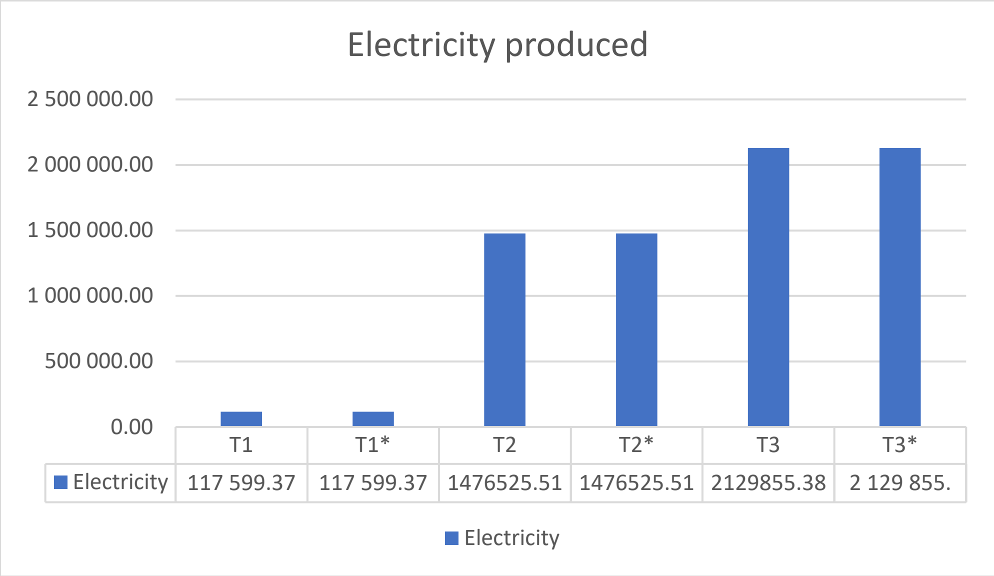


Figure 17 Electricity produced during the whole lifetime of the project (elaborated by the author)

With a CoC of 23.5%, the LCOE would rise to 1.35 $/kWh, but the PBP would reduce to 4.15 years.

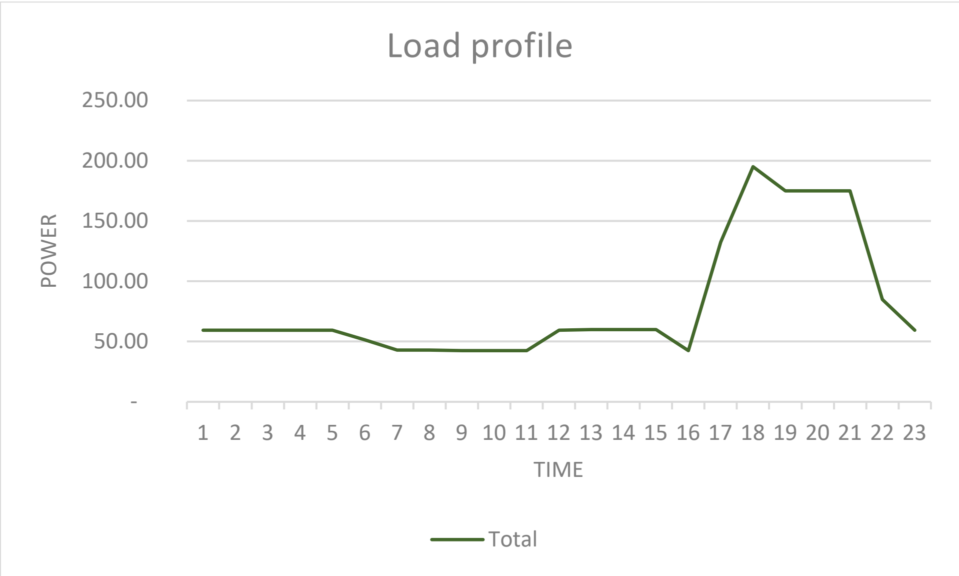


Figure 18 Load profile T2 (elaborated by the author)

The second load, T2 is modelled upon a higher demand, the general structure of the load curve is similar and consistent with what we could observe in the literature. An important peak during the evening - the main rationale behind the utilisation of batteries -, and a slighter peak during the morning.

We identified an average consumption of 1.9 kWh per household. Which results in a load of 5535.99 kWh for the whole community. The sizing resulted in a 113 kW solar system with a 44 069.83 Wh storage system. CAPEX is 172117.00 $, while OPEX is 172117 $. Total expenditure is therefore 221824,4$.

LCOE was estimated at 0.2 cts$/kWh. PBP is therefore 7.88 years. Whereas the energy produced during the full duration of the project is 1 476 525,51 kWh. These computations assumed a CoC of 10.5% if we used instead a CoC of 23.5% the results would change in the following way. The LCOE would rise to 0.38 $/kWh, and the PBP would diminish to 3.75 years.

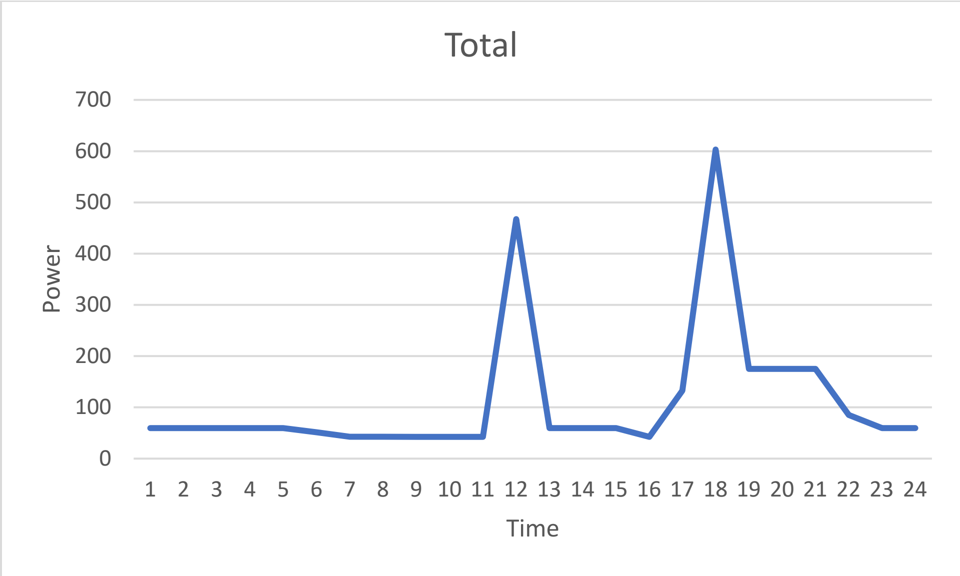


Figure 19 Load profile T3 (elaborated by the author)

The third load, T3, is highly influenced by the presence of the electric stove, the only high-wattage appliance in the household. In fact, two major peaks can be observed, and they correspond to the utilisation of the electric stove, albeit the general structure of the curve will stay the same. The daily load per household for this typology T3 is 2.71 kWh per household, which results in a daily load of 7912.99 kWh for the whole community. The sizing resulted in a 163 kWh solar system, equipped with 65941,58 Wh storage capacity. The lifetime of the project is 25 years in all typologies. CAPEX is estimated to be 224979.43 $, while OPEX is estimated to be 73733.5636 $, the total cost is thereby 298712.99$. LCOE is 0.18 $/kWh. PBP is 7.78 years. The total energy produced is 2 129 855,38 kWh. While assuming a CoC of 23.5% the PBP would be reduced to 3.69 years, and the LCOE would increase to 0.36 $/kWh.

According to the ISE institute (Fraunhofer ISE, 2021), the average LCOE for a medium-sized solar PV with storage capacity would go from 0.09 to 0.24 $ cents/kWh in Germany. A medium capacity is defined as higher than 30 kWp but lower than 1 MW.

4.2.1 Cash Flows

Net Cash flows (CF) would vary significantly according to the LCOE. For T1 the CF would be 132057.73 $, with a CoC of 10.5%. Considering a CoC of 23.5% would yield a different result. The CF would amount to 162372.05 $.

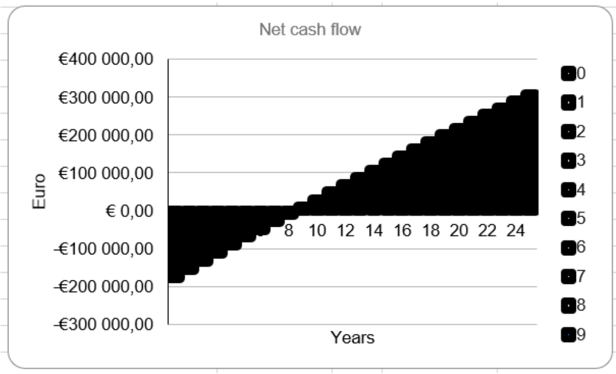


Figure 20 Net cashflows for T1 with 10.5 CoC (elaborated by the author)

The graphic above shows that, assuming a CoC of 10.5% the modelled MG for T1 would need 8 years to generate revenues.

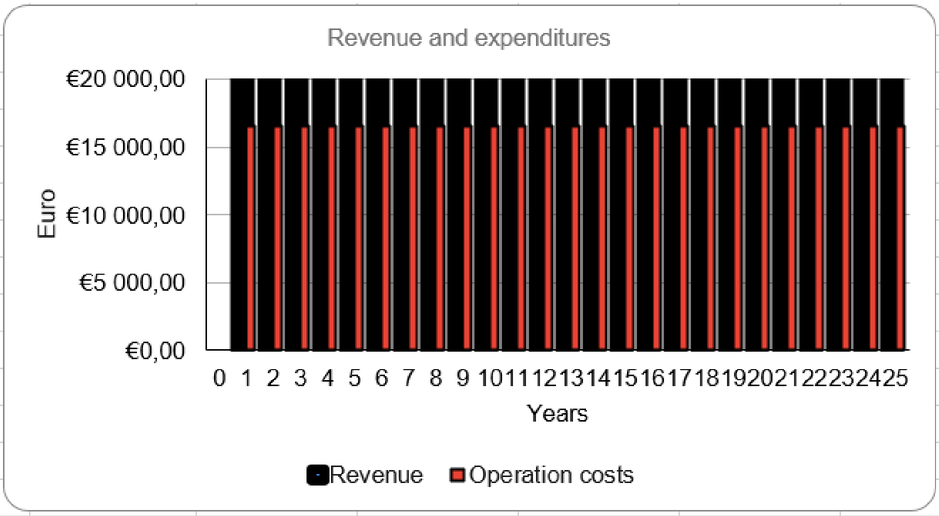


Figure 21 Revenue and expenditure (elaborated by the author)

Figure 21 illustrates that revenues are higher than operational costs. This is the case for every typology.

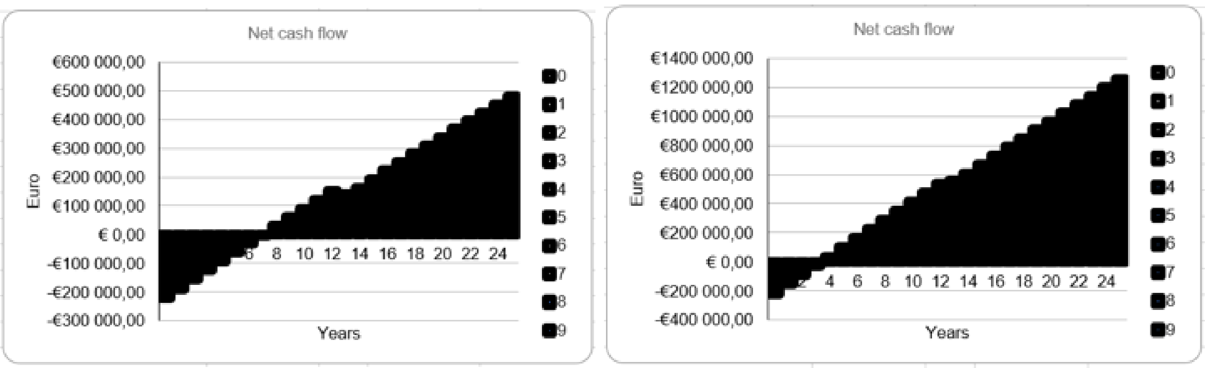


Figure 22 Cash flows for T2 (left) and T2* (right) (elaborated by the author)

While for T2, CF would be $ 482022.25, for T2* it would increase to $ 1258197.46, as illustrated by Figure 22, this would allow to generate revenue, starting from year 4, in T2 and year 8 in T2*.

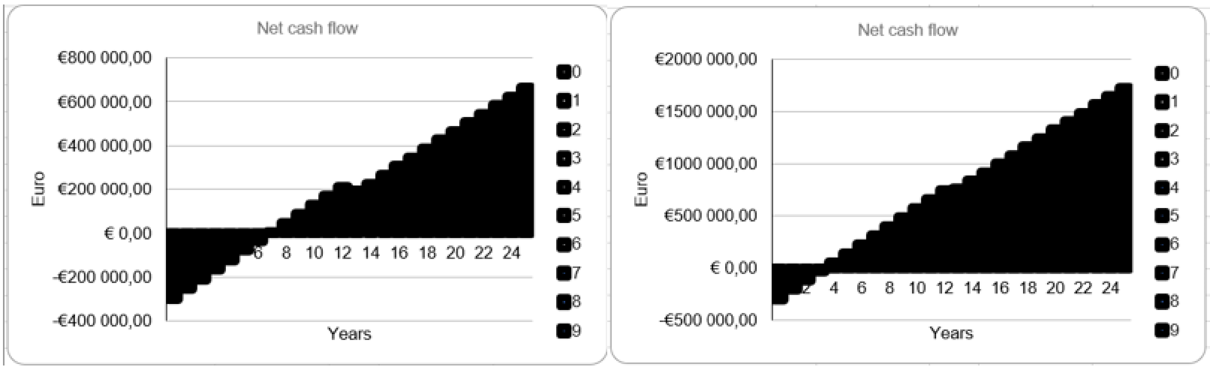


Figure 23 Cash flows for T3 (left) and T3*(right) (elaborated by the author)

While for T3, CF would be 661684,17$, and it would increase to 1727036,72$ for T3*. T3 would start generating revenue from year 6 as shown in Figure 23.

4.3 Scenarios

The three scenarios modelled in section 3.2.7 will be analysed in this section. Scenarios will be solely applied to T3. T3 is the highest consumption model, therefore the main focus will be on the latter. Nevertheless, T2 and T3 yielded very similar LCOE. The results of scenarios for T2 can therefore be forecasted intuitively.

4.3.1 First scenario, subsidies

The first scenario will be applied to T3. The percentage change between the two LCOEs (0.05 $/kWh and 0.18$/kWh). Is 73%, which means that a 73% subsidy should be applied for the LCOE to attain the desired level. Furthermore, this can be quantified economically as we know the total expenditure, which represents 393 934,44$, accounting for a CoC of 10.5%. The subsidy needed to yield an LCOE of 0.05 kWh/$. Through Equation 14 we can therefore estimate the subsidy to represent 287 572,26$.

Undertake a comparison between the subsidies in our scenario and the real subsidies applied by the government of DRC is possible, by applying the same equation (World Bank, 2020) provide data on the average tariffs for electricity (7cts) and on the cost faced by the national utility to provide the service (16 cts/kWh for medium voltage and 21cts/kWh for low voltage). The percentage change from 0.07 to 0.16 is 56%, while the percentage change from 0.07 to 0.21 is 67%. It is possible to deduct the percentual representation of the subsidies applied by the government of DRC. However, quantifying it economically is utterly complex since we do not dispose of grid costs.

4.3.2 Second scenario with diverse CoC, sensitivity analysis

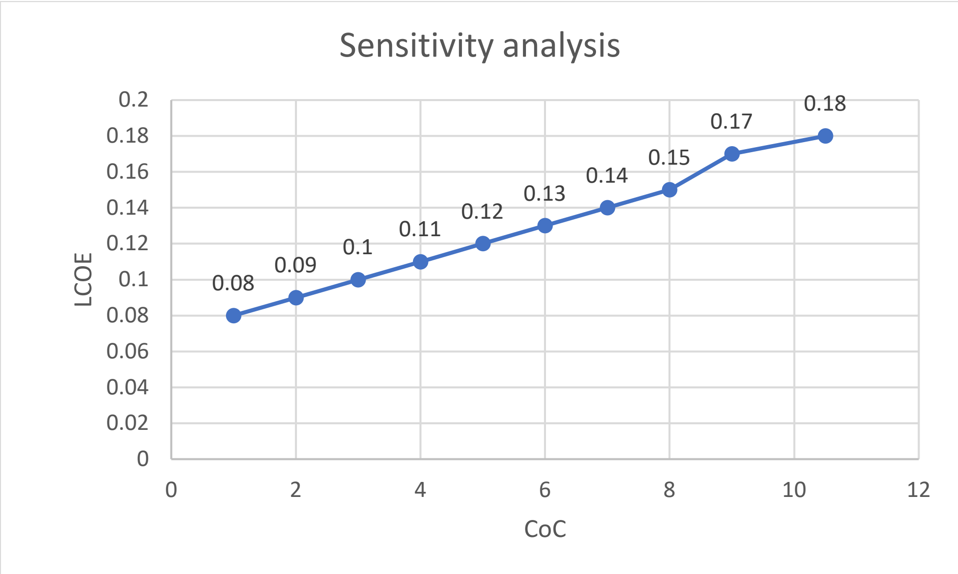


Figure 24 Sensitivity analysis of LCOE to Cost of Capital (elaborated by the author)

A sensitivity analysis of LCOE to CoC was performed. The results are illustrated in Figure 24. CoC values were tested from 1 to 10.5.

4.3.3 Third scenario, combining measures

As highlighted in section 3.2.7.3, batteries and inverters were financed by subsidies offered by the government in this scenario, simultaneously, a reduction in CoC is proposed. 8% is chosen as the starting point since a uniform CoC is a very common assumption in literature for the Global South.

Subsidising both batteries and inverters alone would yield an LCOE as low as 0.12 $/kWh. Adding to this a 2.5% reduction of CoC, bringing the CoC from 10.5% to 8% would further lower the LCOE to 0.10 $/kWh and reduce the total costs to 159 575,56 $. The same result in terms of LCOE is achievable by only subsidising batteries, which would represent an economy of about 14 000$.

4.4 CO_2 Analysis

As stated in previous sections, the results will only be applied to T3. Before computing environmental costs for electricity generation according to Equation 15 and Equation 16, it is necessary to define the parameter "B" from Equation 16. Knowing that a 20-kWh storage capacity would result in 88g of CO_2 and that the storage capacity for T3 corresponds to 65 kWh it is simple to deduct that the CO_2 emissions related to the exploitation of storage capacity amount to 286 gCO_2eq.

According to Equation 15 and Equation 16, environmental costs for electricity generation can be expressed as follows:

991,5011 * 1.27 = 1259.2 $kgCO_2eq$ per household per year (h/y)
991,5011 * 0.006 + 0.286= 6.23 $kgCO_2eq$ per household per year (h/y)

It is now possible to obtain the social cost of CO_2 by converting the results presented above in tonne and by multiplying them by the social cost of CO_2, that latter has been estimated to 185$, as stated in section 3.2.8. Which would translate to a social cost of CO_2 of respectively:

1.259 *185 = 232.91$/h/y

0.00623 * 185 = 1.15 $/h/y

The difference is extremely significant. We can highlight a saving in CO_2 emissions corresponding to 1252.97 $kgCO_2eq$ per year, per household. In a community of 2912 households, this would represent a saving of 3649 tCO_2eq for the whole community. The avoided social cost of emitted CO_2 for the whole community would therefore be 675 065$. However, the actual price of carbon in the market is much lower than the social cost of carbon estimated by scholars. According to USAID carbon credits for decentralized solar fluctuated between 1 and 30$, with an average of 11$ in the VCM.

5. Discussion

Findings from this study should be of key interest to policy makers, grid operators, and local municipalities interested in understanding the techno-economic potential of solar energy communities in the DRC as well as the private sector is developing business models. We discuss the implications of the findings from different points of view.

5.1 Techno-economic implications

The calculations show that the consumption profiles have a huge impact on the LCOE. The LCOE values yielded for T1 and T1* are high, this explains the short PBP for T1*. An LCOE of 0.71 $/kWh would not be affordable for most countries. Moreover, projects situated in those price ranges usually provide higher energy, for a higher number of people. As an illustration, according to the IEA (IEA, 2020), in the US a wind offshore plant (600 MW), produces energy with an LCOE of 0.71$/kWh. Obviously, the conditions are different so the comparison may not be pertinent, nevertheless, this cost is too elevated for a 9kW solar plant. Furthermore, since this plant would only allow for lighting and phone charging, it is fair to assume that its utilisation would be destined for low-income households with a lower ATP. The elevated LCOE is probably due to the relatively low amount of energy produced. The total energy produced over the whole lifetime of T1 is only 117 599,38 kWh. From this perspective, T2 is more interesting as it allows for satisfying a higher demand, consequently producing more energy, at a lower cost. Total energy produced increased by more than 12 times, attaining 1 476 525,50 kWh per year. Which reduced significantly the LCOE bringing it to 0.20 $/kWh. The PBP diminished slightly for T2, while for T2*, PBP is low, but the yielded LCOE (0.38$/kWh) is not affordable for rural households in DRC. T3 yielded a slightly lower LCOE (0.18$/kWh), with an increase of more than 30% concerning production, attaining 2 129 855,38 kWh. While PBP stands around 7.78 for T3. T3* is again too elevated to be affordable, this shows the impact of interest rate and CoC on overall system costs. While T1 is not economically viable, electrifying lower tiers of electricity demand before higher ones could be a strategy for the government. However, in the case study, we modeled T2's costs are higher than T3's. As T3 would allow for the satisfaction of higher demand, it may be more pertinent to implement directly T3. Last but not least, an LCOE of 0.18$/kWh is likely to be too elevated for people living in rural areas of DRC. From this perspective, an effective business model could deliver a major impact on the project's viability, people's livelihood, and well-being.

Furthermore, the calculations with different scenarios of subsidy and cost of capital have different implications. First, calculations in section 4.3.1 illustrated that the PV system can provide electricity at a lower cost, compared to the grid. Therefore, redirecting part of the subsidies allocated to the grid to solar installations consequently seems to be an interesting option for zones unserved by the grid in DRC. This analysis quantitatively demonstrates the concept of the "subsidy burden", evocated in section 1.2.2. The second scenario illustrated that CoC exerts a substantial effect on LCOE. However, the reduction in LCOE attributable to a diminution of CoC is not sufficient for the LCOE to be affordable. The third scenario demonstrated that the sole presence of batteries almost doubles the LCOE. It is therefore important to highlight that coupling the subsidy for batteries with a reduction in CoC leads to an impressive diminution of LCOE.

5.2 Findings and implications for business-models

In this section, we discuss several business models that can address the elevated LCOE, and increase ATP & WTP, thus allowing people to access electricity at an affordable price.

Considering that most solar microgrids are financed by private entities (IEA, AFDB, 2023), it is crucial to explore the possibility of a community adopting a different business model. Typically, a private entity would incur initial costs, enabling the community to access electricity by paying a tariff based on household consumption. Determining an appropriate tariff often necessitates studies on "Willingness to Pay" (WTP) and "Ability to Pay" (ATP). When the electricity tariff enforced by law is considered (7 cts), the project appears financially unfavourable. This suggests that profitability in the absence of government support is challenging to attain in the DRC, as sustaining such a high tariff (0.18 $/kWh) for the population is likely to be unfeasible. New business models that do not put profitability at the core of their business need to be found. Nevertheless, on the true spirit of an energy community as a social innovation tool, energy communities have the potential to change this paradigm and lead towards the development of social capital, capacity building, and increased energy democracy, eventually contributing to the realisation of a "just energy transition"; while providing electricity at an affordable cost, thus increasing energy security (Ambole et al., 2021; Sovacool et al., 2020).

(Mukoro et al., 2022) provide a systematic review of business models in SSA. A plethora of different business models exist, the most frugal are Pay-as-you-go, lease-to-own, and pay-per-service-unit. The Pay-as-you-go method involves the prepayment for electricity services in the perspective of using it. In the lease-to-own model, individuals rent a service, and the funds allocated for the rent contribute towards ownership of the service, eventually leading the end-user(s) to possess the good. The third option, pay-per-service-unit, is characterized by the advantageous feature of liberating users from the financial burdens associated with service provision. As an illustration, connection fees from SNEL[10] can attain 500$, which is a substantial amount of money for individuals with a low purchase power in rural settings of DRC. Energy as a service therefore allows for avoiding high upfront costs. Nevertheless, this model raises additional inquiries, as there remains uncertainty regarding whether individuals will possess adequate financial resources to take ownership and shoulder the associated costs. There is a clear demand for innovative business models and alternative financial mechanisms to mobilize funds, addressing this pressing challenge (International Energy Agency, 2023).

5.3 Ecological implications: CO_2 analysis and Carbon market

The CO_2 analysis in section 4, showed that this electrification method would represent a saving of 3649 tCO_2eq per year, for the whole community. Those savings could be leveraged in VCM (voluntary carbon market) as a way to contribute to financing electrification efforts. However, Carbon Clear and USAID (Carbon Clear, 2023) highlighted that revenues in the VCM are low, consequently, as of today it can only be considered an additional revenue and not the main source of revenue of the firm (Carbon Clear, 2023). DRC presents significant avoided CO_2 potential which could be exploited in case of further development of the VCM market.

5.4 Policy implications and recommendations

The energy sector in DRC is heavily subsidised, with over 60% of the electricity tariff being subsidized by the government, and the possibility of introducing additional subsidies is limited, due to significant financial support of the government. The reallocation of the present subsidies is possible. Our results show that the government should increase its share of solar assets both in rural and urban settings, proposing different business models which adequate for end-users' financial situation. Some of the individuals and business activities in urban settings will have a higher ATP and, consequently higher solvability, eventually leading to an increased revenue stream. Part of the subsidies allocated to the grid could be reallocated to solar in urban zones where the grid showed less reliability. For rural settings subsidizing the batteries could generate substantial savings. Mapping the territory of DRC in terms of ATP and WTP would be extremely beneficial for policymakers as it would allow for a decentralised approach to electrification. Another option, in a long-term perspective, would be to act on ATP. If costs cannot be reduced people's revenues can be enhanced, eventually allowing them to afford slightly higher prices.

Reducing CoC is central to allowing small firms to attract capital. In order to reduce the CoC the perceived risk has to be lowered, moreover the use of ESG criteria tends to disadvantage DRC. From this standpoint election in DRC in December 2023 will play a pivotal role (Ameli et al., 2021). Positive performance of firms could contribute to lowering CoC (Ameli et al., 2021). Addressing the natural monopoly of SNEL is of paramount importance, concurrence is allowed but institutions should work to create an enabling environment for companies to invest.

Community energy can play a pivotal role in policies – both in the long and the short term. Community energy is likely to provide electricity while stimulating demand through productive uses. Local food production and commercial activities will both contribute to demand stimulation (fundamental for utilities'

[10] https://globalpressjournal.com/africa/democratic-republic-of-congo/accessing-electricity-drc-expensive-pirating-power-comes-dangerous-cost/en/

economic viability) and a reduction of living costs[11]. Fundings in solar could yield positive externalities on the global production of the country as they would provide electricity, which would enable other commercial activities.

Lastly, when conducting the study, it is evident that data scarcity exists with regard to consumption profiles. Policymakers should therefore address data scarcity in DRC to increase the quality and robustness of the analyses. The energy sector could benefit from the availability of a deeper granularity of data, which would enable universities and think tanks to provide thorough in-depth analysis.

5.5 Limitations and future work

Different assumptions with scientific justification were posited throughout this work, due to data scarcity existing in the region the only way to deal with data scarcity is by making assumptions, nonetheless, all assumptions were justified scientifically. Primarily, we did not account for load evolution while sizing the solar system, nevertheless, forecasting load evolution is an extremely difficult exercise, especially in rural areas (Mandelli, 2016) Secondly, demand was modelled according to nominal power instead of duty cycles, which could lead to data that are prone to overestimation. However, the granularity of data in our possession would not allow for modeling this level of detail. Furthermore, we only considered basic appliances, this is therefore very unlikely to have a significant impact on demand estimation. Thirdly, households in SSA often utilise second-hand appliances which tend to have lower efficiency (IEA, 2022), which could slightly increase demand. The increase is negligible, conversely, it is important to address the awareness of this fact concerning the context of SSA.

Future work could extend the scope of this research to the commercial and industrial sectors and focus also on urban settings. Further analysis of future demand scenarios could be provided. Particularly, energy demand in SSA is destined to increase due to the increase in population and the new end-uses. Despite this expected increase in energy demand, as underlined in Section 2 energy demand in SSA is characterized by considerably low consumption. Therefore, imaging ways to stimulate this demand, especially in rural settings, is fundamental. One is without any doubt productive uses. Some scholars consider that productive uses should be accounted for in the demand of households as these activities could be small businesses and other "small" activities like irrigation that could be linked to substantial survival of people (Dagnachew et al., 2023). Productive uses are without any doubt an element that needs to be taken into consideration but since for the scope of this work we decided to focus solely on the residential sector, albeit a separation between these two sectors would be purely artificial; we will operate the latter for heuristic purposes, rather than expressing an element present in reality.

Last but not least, scholars and international organisations assert that cooling demand will rise considerably in SSA (IEA, 2022, 2022a), especially in DRC (Miranda et al., 2023). The utilisation of air cooling would most likely correspond to the peak power of solar PV, which might make it simpler for the country to address this load through solar energy (Laine et al., 2019). However, this would necessitate a large penetration of AC to be applicable for residential demand; as shown by Falchetta (Falchetta & Mistry, 2021), this is not very likely to happen in the residential sector of DRC. The option remains valid for commercial and industrial customers, albeit if penetration stays as low as today's rate (2.6%) the impact of AC would be minimal. However, this option would require the presence of a reliable grid option, which is absent in DRC, as of today. Grids in DRC need to undergo significant improvements(Sterl et al., 2023). Future work can entail LCOE analysis with cooling appliances, Figure 25 shows the potential increase in load if cooling penetration level increased.

---

[11] Food is one of the main expenditures in households and in DRC it is subject to strong inflation. https://microdata.worldbank.org/index.php/catalog/4490

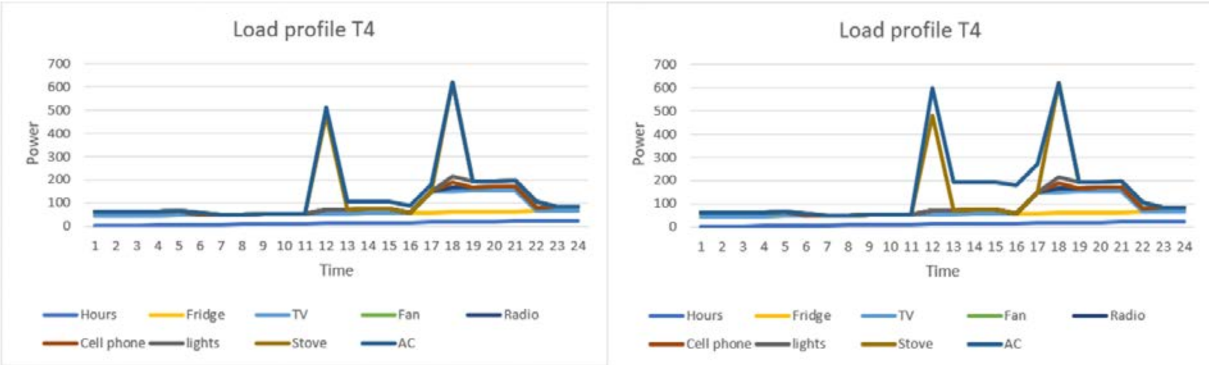


Figure 25 Load profile of T4 assuming an AC penetration level of 2.6% (left). Load profile of T4 assuming an AC penetration level of 10% (right) (elaborated by the author)

6. Conclusions

Energy community or renewables on a community scale is an important opportunity for rural Sub-Saharan Africa. Nevertheless, assessing the impact from the energetic, economic, and environmental standpoint requires addressing the substantial research gaps encountered when analysing the energy sector of the Democratic Republic of the Congo (DRC). Resources in the literature concerning electricity demand and costs related to PV production in sub-Saharan Africa are limited, if not non-existent, for some countries like DRC.

Against this background, to address the gaps, we developed a methodology that allowed us to develop a dataset containing electricity demand estimations. These datasets include data from UN-Habitat, UNICEF, Renewable Ninja, JRC (European Commission), and the government of DRC. Later using the electricity consumption, production, and storage characteristics, we performed a levelized cost of energy (LCOE) for DRC. We did this analysis with different consumption typologies, subsidies, and cost capital, and provided sensitivity analysis with diverse scenarios. The results show that a 163-kW solar system with a storage capacity of 65 kWh could satisfy the residential load of the modelled community at an LCOE of 0.18 $/kWh. Environmental impact was also measured through CO_2 analysis, which resulted in significant savings in carbon dioxide emissions, compared to the alternative electricity generation source, namely diesel generators. 3649 tCO_2eq of emissions are avoided by utilising microgrids instead of diesel generators. Relying on those calculations it was possible to provide recommendations for policymakers for example for subsidies (reallocation of subsidies, developing an enabling environment for firms to invest, consequently reducing the cost of capital, providing grants to subsidise the most expensive component of the solar system) as well as discuss the implication for different business models.

We can conclude that the impact on energetic, economic, and environmental levels, can be considered positive overall, the energy produced allows to satisfy the estimated demand, and the yielded LCOE related to this demand is lower than the cost of generating low voltage electricity from the grid and potential for avoided CO_2 is vast. The only limit usually linked with PV production is land occupation but since DRC's population density is scarce, we believe that it is currently a negligible aspect if PV implementation is planned wisely.

7. Bibliography

ABDELRAZIK, M. K., ABDELAZIZ, S. E., HASSAN, M. F., & HATEM, T. M. (2022). Climate action: Prospects of solar energy in Africa. *Energy Reports*, *8*, 11363–11377. https://doi.org/10.1016/j.egyr.2022.08.252

ACMI. (2022). Africa Carbon Markets Initiative (ACMI): Roadmap Report. Harnessing carbon markets for Africa Retrieved April 4, 2023, from https://www.seforall.org/system/files/2022-11/ACMI_Roadmap_Report_Nov_16.pdf.

ADHIKARI, S., LUTZ, W. , & K.C., S. (2023). Rural/urban fertility differentials in the Global South: Is female education the key driver of declining birth rates? *IIASA Working Paper*. Laxenburg, Austria: WP-23-004

ADORNETTO, T. (2022). Energy Trajectories and Solar Energy Imaginaries of the Maasai. *Ufahamu: A Journal of African Studies*, 43(1). http://dx.doi.org/10.5070/F743156313 Retrieved from https://escholarship.org/uc/item/0t25r3z8

AGUTU, C., EGLI, F., WILLIAMS, N. J., SCHMIDT, T. S., & STEFFEN, B. (2022). Accounting for finance in electrification models for sub-Saharan Africa. *Nature Energy*, *7*(7), Article 7. https://doi.org/10.1038/s41560-022-01041-6

AKINBULIRE, T.O., OLUSEYI, P.O. & BABATUNDE, O.M. (2014). Techno-economic and environmental evaluation of demand side management techniques for rural electrification in Ibadan, Nigeria. *Int J Energy Environ Eng* **5**, 375–385. https://doi.org/10.1007/s40095-014-0132-2

AKINYELE, D. O., & RAYUDU, R. K. (2016). Comprehensive techno-economic and environmental impact study of a localized photovoltaic power system (PPS) for off-grid communities. *Energy Conversion and Management*, 124, 266-279. https://doi.org/10.1016/j.enconman.2016.07.022

AMBOLE, A.; KORANTENG, K.; NJOROGE, P.; LUHANGALA, D.L. (2021). A Review of Energy Communities in Sub-Saharan Africa as a Transition Pathway to Energy Democracy. *Sustainability, 13, 2128*. https://doi.org/10.3390/su13042128

AMELI, N., DESSENS, O., WINNING, M., CRONIN, J., CHENET, H., DRUMMOND, P., CALZADILLA, A., ANANDARAJAH, G., & GRUBB, M. (2021). Higher cost of finance exacerbates a climate investment trap in developing economies. *Nature Communications, 12(1), 1-12*. https://doi.org/10.1038/s41467-021-24305-3

ANG, B., CHOONG, W., & NG, T. (2015). Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews*, *42*, 1077-1093. https://doi.org/10.1016/j.rser.2014.10.064

ANNUAIRE STATISTIQUE RDC. (2020). *Congo: National Statistical Office*, Kinshasa.

ANOUNE, K., BOUYA, M., ASTITO, A. et BEN ABDELLAH.A. (2018). Sizing Methods and Optimization Techniques for PV-Wind Based Hybrid Renewable Energy System: *A Review. Renewable and Sustainable Energy Reviews 93 (October): 652-73*. https://doi.org/10.1016/j.rser.2018.05.032.

ARRETE MINISTERIEL n° 005/CAB/MIN-ECONAT&COM/2009 du 7 mars 2009 portant fixation des tarifs de vente d'énergie électrique par la Snel pour ses abonnés haute tension, moyenne tension et basse tension.

AUTORITE DE REGULATION DU SECTEUR DE L'ELECTRICITE (ARE). (2022). *Rapport annuel.* https://are.gouv.cd/wp-content/uploads/2023/05/ARE-RAP-2022-RAPPORT-ANNUEL-2022-6.pdf

BABATUNDE O. M., EMEZIRINWUNE, M., DENWIGWEL, H., and AKIN-ADENIYI, J. (2017).«Hybrid power system for off-grid communities: Techno-economic and energy mix analysis,» *2017 IEEE 3rd International Conference on Electro-Technology for National Development (NIGERCON)*, Owerri, Nigeria, pp. 946-952, doi: 10.1109/NIGERCON.2017.8281960.

BALABANYAN, A., SEMIKOLENOVA, Y., HANKINSON, D., NASH, S. and C. PARCELS. (2021). African Utilities during COVID-19: Challenges and Impacts. *ESMAP Papers*. Washington, DC: World Bank.

BARABINO, E., FIORITI, D., GUERRAZZI, E., MARIUZZO, I., POLI, D., RAUGI, M., RAZAEI, E., SCHITO, E., & THOMOPULOS, D. (2023). Energy Communities : A review on trends, energy system modelling, business models, and optimisation objectives. *Sustainable Energy, Grids and Networks*, *36*, 101187. https://doi.org/10.1016/j.segan.2023.101187

BASSAM, N. E., & MAEGAARD, P. (2004). *Integrated renewable energy for rural communities: Planning Guidelines, Technologies and Applications*. Elsevier.

BIELIG, M., KACPERSKI, C., KUTZNER, F., & KLINGERT, S. (2022). Evidence behind the narrative: Critically reviewing the social impact of energy communities in Europe. *Energy Research & Social Science, 94, 102859*. https://doi.org/10.1016/j.erss.2022.102859

BILICH, A., LANGHAM, K., GEYER, R., GOYAL, L., HANSEN, J., KRISHNAN, A., BERGESEN, J., & SINHA, P. (2017). Life Cycle Assessment of Solar Photovoltaic Microgrid Systems in Off-Grid Communities. *Environmental Science & Technology*, *51*(2), 1043-1052. https://doi.org/10.1021/acs.est.6b05455

BLACK J., HASHIMZADE N., & MYLES G. (2009). *Oxford Dictionary of Economics* (Third edition). Oxford University Press.

BRUMMER, V. (2018). Community energy – benefits and barriers: A comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. *Renewable & Sustainable Energy Reviews, 94, 187–196*. https://doi.org/10.1016/j.rser.2018.06.013

CARAMIZARU, A. and UIHLEIN, A. (2020). *Energy communities: an overview of energy and social innovation,* EUR 30083 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-10713-2, doi:10.2760/180576, JRC119433.

CARBON CLEAR. (2023) *Carbon Credits for Off-grid Solar in Sub-Saharan Africa Lessons from Energy-access Companies in the Voluntary Carbon-credit Market*. USAID.

CARVALHO, A. P. O., RIQUITO, M., & FERREIRA, V. (2022). Sociotechnical imaginaries of energy transition: The case of the Portuguese Roadmap for Carbon Neutrality 2050. *Energy Reports*, *8*, 2413–2423. https://doi.org/10.1016/j.egyr.2022.01.138

CENTRAL BUREAU OF STATISTICS (CBS). (2017) *Multiple Indicator Cluster Survey 2017,* Survey Finding Report.

CHAKRAVORTY, U., EMERICK, K., & LEAH-RAVAGO, M. (2016). Lighting up the last mile: the benefits and costs of extending electricity to the rural poor. *Social Science Research Network*. https://doi.org/10.2139/ssrn.2851907

CLIMATE WATCH, (2020). *World Resources Institute (WRI)*.

CLOKE, J., MOHR, A., & BROWN, E. (2017). Imagining renewable energy : Towards a Social Energy Systems approach to community renewable energy projects in the Global South. *Energy Research & Social Science*, *31*, 263-272. https://doi.org/10.1016/j.erss.2017.06.023

COLE, M. A., ELLIOTT, R. J., OCCHIALI, G., & STROBL, E. (2018). Power outages and firm performance in Sub-Saharan Africa. *Journal of Development Economics*, *134*, 150–159. https://doi.org/10.1016/j.jdeveco.2018.05.003

DAGNACHEW, A.G., CHOI, SM. & FALCHETTA, G. (2023). Energy planning in Sub-Saharan African countries needs to explicitly consider productive uses of electricity. *Sci Rep* 13, 13007. https://doi.org/10.1038/s41598-023-40021-y

DAGNACHEW, A. G., LUCAS, P. L., HOF, A. F., GERNAAT, D. E., De BOER, H. S., & VAN VUUREN, D. P. (2017). The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa – A model-based approach. *Energy*, *139*, 184–195. https://doi.org/10.1016/j.energy.2017.07.144

DEPURU, S. S. S. R., WANG, L., & DEVABHAKTUNI, V. (2011). Electricity theft: Overview, issues, prevention and a smart meter-based approach to control theft. *Energy Policy*, *39*(2), 1007–1015.

DEVORE, J. L. (2012). *Probability and statistics for Engineering and the Sciences*. Cengage Learning. Eight edition.

DUFO-LÓPEZ, R., ZUBI, G., & FRACASTORO, G. V. (2012). Tecno-economic assessment of an off-grid PV-powered community kitchen for developing regions. *Applied Energy, 91(1), 255-262*. https://doi.org/10.1016/j.apenergy.2011.09.027

EDOMAH, N. (2022). Rural electrification in Africa: a case study of Yebu community solar minigrid. *Environmental Research: Infrastructure and Sustainability*, *2*(4), 045001. https://doi.org/10.1088/2634-4505/ac9014

EGLI, F., Agutu, C., STEFFEN, B., & SCHMIDT, T. S. (2023). The cost of electrifying all households in 40 Sub-Saharan African countries by 2030. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-40612-3

EGLI, F., STEFFEN, B., & SCHMIDT, T. S. (2019). Bias in energy system models with uniform cost of capital assumption. *Nature Communications*, *10*(1), 1-3. https://doi.org/10.1038/s41467-019-12468-z

EKO, J. O., et MANOSH C. P. (2021). Integrated Sustainable Energy for Sub-Saharan Africa: A Case Study of Machinga Boma in Malawi. *Energies* 14 (19): 6330. https://doi.org/10.3390/en14196330.

ESMAP (2015). *BEYOND CONNECTIONS, Energy Access Redefined*. ESMAP. Retrieved from https://mtfenergyaccess.esmap.org/data/files/download-documents/full_report_beyond_connection.pdf

ESMAP. (2017). *Benchmarking Study Of Solar Pv Mini Grids Investment Costs*. The World Bank. Retrieved August 10, 2023, from https://documents1.worldbank.org/curated/ru/569621512389752401/pdf/121829-ESM-PVHybridminigridsCostingbenchmarkTTAESMAPConfEdtemplateDecv-PUBLIC.pdf.

EUROPEAN COMMISSION. (2022). *REPowerEU: Joint European Action for more affordable, secure and sustainable energy*.

EUROPEAN COMMISSION. Directorate General for Energy. (2019). *Clean Energy for All Europeans. LU:* Publications Office. https://data.europa.eu/doi/10.2833/21366

FALCHETTA, G., & MISTRY, M. N. (2021). The role of residential air circulation and cooling demand for electrification planning: Implications of climate change in sub-Saharan Africa. *Energy Economics, 99, 105307*. https://doi.org/10.1016/j.eneco.2021.105307

FLOURIOT, J. (2008). Congo RDC : Population et aménagement d'un immense pays. *Population et Avenir*, 687(2), 4. https://doi.org/10.3917/popav.687.0004

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE. *Levelized Cost of Electricity - Renewable Energy Technologies* - Fraunhofer ISE. (2021). Retrieved the 24th November 2023, https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html

FRISCHKNECHT, R., P. STOLZ, L. KREBS, M. de WILD-SCHOLTEN, P. SINHA, V. FTHENAKIS, H.C. KIM, M. RAUGEI, M. STUCKI. (2020). *Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems*, INTERNATIONAL ENERGY AGENCY (IEA). (IEA) PVPS Task 12, Report T12-19:2020.

FUSO NERINI, F., TOMEI, J., TO, L.S. *et al.* (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat Energy 3, 10–15* https://doi.org/10.1038/s41560-017-0036-5

GENUS, A., ISKANDAROVA, M., GOGGINS, G., FAHY, F., & LAAKSO, S. (2021). Alternative energy imaginaries: Implications for energy research, policy integration and the transformation of energy systems. *Energy Research & Social Science, 73, 101898*. https://doi.org/10.1016/j.erss.2020.101898

GIZ. (2016). *What size shall it be? A guide to mini-grid sizing and demand forecasting.* https://www.giz.de/en/downloads/Sizing_handbook_150dpi_for_web.pdf

GUILLOU, E., & GIRARD, B. (2023). Mini-Grids at the Interface: The Deployment of Mini-Grids in Urbanizing Localities of the Global South. *Journal of Urban Technology, 30(2), 151–170.* https://doi.org/10.1080/10630732.2022.2087170

HALLEUX. (2015). "Les Territoires Périurbains et leur Développement dans le Monde : un Monde en Voie d'Urbanisation et de Périurbanisation," in BOGAERT, J. et HALLEUX, J-M. eds, *Territoires Périurbains: Développement, Enjeux et Perspectives dans les Pays du Sud.* Gembloux: Presses agronomiques de Gembloux).

HEINISCH, V., ODENBERGER, M., GÖRANSSON, L., & JOHNSSON, F. (2019). Organizing prosumers into electricity trading communities: Costs to attain electricity transfer limitations and self-sufficiency goals. *International Journal of Energy Research.* https://doi.org/10.1002/er.4720

HERNANDEZ, R. R., EASTER, S. B., MURPHY-MARISCAL, M. L., MAESTRE, F. T., TAVASSOLI, M., ALLEN, E. B., BARROWS, C. W., BELNAP, J., OCHOA-HUESO, R., RAVI, S., & ALLEN, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews, 29, 766-779.* https://doi.org/10.1016/j.rser.2013.08.041

HUBBLE, A. H., & USTUN, T. S. (2016). Scaling renewable energy based microgrids in underserved communities: Latin America, South Asia, and Sub-Saharan Africa. *IEEE PES PowerAfrica, Livingstone, Zambia,.* https://doi.org/10.1109/powerafrica.2016.7556586

IEA, IRENA, UNSD, World Bank, WHO. (2023). *Tracking SDG 7: The Energy Progress Report.* World Bank, Washington DC.

INTERNATIONAL ENERGY AGENCY (IEA). (2023), *Financing Clean Energy in Africa*, IEA, Paris https://www.iea.org/reports/financing-clean-energy-in-africa, License: CC BY 4.0

INTERNATIONAL ENERGY AGENCY (IEA). (2023), *Cost of Capital Observatory*, IEA, Paris https://www.iea.org/reports/cost-of-capital-observatory, License: CC BY 4.0

INTERNATIONAL ENERGY AGENCY (IEA). (2022a). *World Energy Outlook* 2022, IEA

INTERNATIONAL ENERGY AGENCY (IEA). (2022). *Africa Energy Outlook* 2022, IEA

INTERNATIONAL ENERGY AGENCY (IEA). (2020). *Levelised Cost of Electricity Calculator*, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-electricity-calculator

INTERNATIONAL ENERGY AGENCY (IEA). (2019). *Africa Energy Outlook 2019*, IEA

INTERNATIONAL ENERGY AGENCY (IEA). *Energy security – Topics - IEA.* (Consulted on April 18th). IEA. https://www.iea.org/topics/energy-security

IPCC. (2012). *Glossary of terms. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [FIELD, C.B., BARROS, V., STOCKER, T.F., QIN,D., DOKKEN, D.J., EBI, K.L., MASTRANDREA, M.D., MACH, K.J., PLATTNER, G.-K., ALLEN, S.K., TIGNOR, M. and MIDGLEY, P.M. (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 555-564.

IPCC.(2022). *Summary for Policymakers* [PÖRTNER, H.-O., ROBERTS, D.C., POLOCZANSKA, E.S., MINTENBECK, K., TIGNOR, M., ALEGRÍA, A., CRAIG, M., LANGSDORF, S., LÖSCHKE, S., MÖLLER, V., OKEM A.(eds.)]. In: Climate change 2022: impacts, adaptation and vulnerability.

Contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change [PÖRTNER, H.-O., ROBERTS, D.C., TIGNOR, M., POLOCZANSKA, E.S., MINTENBECK, K., ALEGRÍA, A., CRAIG, M., LANGSDORF, S., LÖSCHKE, S., MÖLLER, V., OKEM, B., & RAMA, B. (eds.)]. Cambridge University Press, Cambridge, New York, pp. 3-33, doi:10.1017/9781009325844.001.

IRENA. (2016). *Solar PV in Africa: Costs and Markets*

IRENA. (2021). *The Renewable Energy Transition in Africa.* https://www.irena.org/publications/2021/March/The-Renewable-Energy-Transition-in-Africa.

IRENA. (2022a), *World Energy Transitions Outlook,* International Renewable Energy Agency, Abu Dhabi.

IRENA. (2022b), *Solar PV: A gender perspective*, International Renewable Energy Agency, Abu Dhabi.

IRENA. (2022c), *Renewable Energy Statistics 2022*, International Renewable Energy Agency, Abu Dhabi.

IRENA and CPI. (2023), *Global landscape of renewable energy finance*, International Renewable Energy Agency, Abu Dhabi.

JAKHRANI, A. Q., OTHMAN, A. K., RIGIT, A. R. H., & SAMO, S. R. (2012). Estimation of carbon footprints from diesel generator emissions. *2012 International Conference on Green and Ubiquitous Technology*

KAKOULAKI, G.; MONER-GIRONA, M. (2020): *Electricity grid Africa.* European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/624c6e71-3b9c-4f48-8c67-645911798d41

KARKOUR, S., RACHID, S., MAAOUI, M., LIN, C.-C., & ITSUBO, N. (2021). Status of Life Cycle Assessment (LCA) in Africa. *Environments*, *8*(2), Article 2. https://doi.org/10.3390/environments8020010

KIBUKILA, N., KAKEZA, M., SAPEMBI, I., LWAMBA, I., MAKENGA, N., SANGWA, N. W., KABULO, M. W., BANZA, B. W., & TSHIKALA, K. (2022). Evaluation of the Maintenance of a Medium Voltage Electricity Distribution Network by the ABC Method: Application in DR Congo. *International Journal of Energy and Environmental Science, 7(6), Article 6*. https://doi.org/10.11648/j.ijees.20220706.11

LAINE, H. S., SALPAKARI, J., LOONEY, E. E., SAVIN, H., PETERS, I. M., & BUONASSISI, T. (2019). Meeting global cooling demand with photovoltaics during the 21st century. *Energy and Environmental Science*, *12*(9), 2706–2716.

LEE, J. T., & CALLAWAY, D. S. (2018). The cost of reliability in decentralized solar power systems in sub-Saharan Africa. *Nature Energy*, *3*(11), Article 11. https://doi.org/10.1038/s41560-018-0240

LEE, K., MIGUEL, E., & WOLFRAM, C. (2016). Appliance Ownership and Aspirations among Electric Grid and Home Solar Households in Rural Kenya. *The American Economic Review*, *106*(5), 89–94. https://doi.org/10.1257/aer.p20161097

LEWIS, F. B. (2015). Costly 'Throw-Ups': electricity theft and power disruptions. *The Electricity Journal,* 28(7), 118–135. https://doi.org/10.1016/j.tej.2015.07.009

LOI ORGANIQUE n° 08/016 du 07 octobre 2008 portant composition, organisation et fonctionnement des Entités Territoriales Décentralisées et leurs rapports avec l'Etat et les Provinces.

LOMBARDI, F., BALDERRAMA, S., QUOILIN, S., & COLOMBO, E. (2019). Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model. *Energy*, *177*, 433–444. https://doi.org/10.1016/j.energy.2019.04.097

LONGE, O. M., OUAHADA, K., FERREIRA, H. C., & CHINNAPPEN, S. (2014). Renewable Energy Sources microgrid design for rural areas in South Africa. In *IEEE PES Innovative Smart Grid Technologies Conference*. https://doi.org/10.1109/isgt.2014.6816378

LONGE, O. M., RAO, N., OMOWOLE, F., OLUWALAMI, A. S., & ONI, O. T. (2017). A Case Study on Off-grid Microgrid for Universal Electricity Access in the Eastern Cape of South Africa. *International Journal of Energy Engineering*, *7*(2), 55–63. https://doi.org/10.5923/j.ijee.20170702.03

LOUIE, H., & DAUENHAUER, P. (2016). Effects of load estimation error on small-scale off-grid photovoltaic system design, cost and reliability. *Energy for Sustainable Development*, *34*, 30-43. https://doi.org/10.1016/j.esd.2016.08.002

MANDELLI, S., MERLO, M., & COLOMBO, E. (2016). Novel procedure to formulate load profiles for off-grid rural areas. *Energy for Sustainable Development*, *31*, 130–142. https://doi.org/10.1016/j.esd.2016.01.005

MARANI, M., KATUL, G. G., PAN, W., & PAROLARI, A. J. (2021). Intensity and frequency of extreme novel epidemics. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(35). https://doi.org/10.1073/pnas.2105482118

MARGUERON, Maël. (2021). *Les effets de l'électrification sur la satisfaction des besoins humains en milieu rural: étude de cas dans la région d'Iringa en Tanzanie*. Mémoire de Master en socioéconomie, Université de Genève.

MATINGA, M. N., & ANNEGARN, H. J. (2013). Paradoxical impacts of electricity on life in a rural South African village. *Energy Policy, 58, 295-302*

MCKENNA, R., (2018). The double-edged sword of decentralized energy autonomy. *Energy Policy*, Volume 113, 747-750.

MIRANDA, N. D., LIZANA, J., SPARROW, S., ZACHAU-WALKER, M., WATSON, P., WALLOM, D., KHOSLA, R., & MCCULLOCH, M. (2023). Change in cooling degree days with global mean temperature rise increasing from 1.5 °C to 2.0 °C. *Nature Sustainability*, *6*(11), 1326–1330. https://doi.org/10.1038/s41893-023-01155-z

MIRZANIA, P., BALTA-OZKAN, N., & FORD, A. (2020). An innovative viable model for community-owned solar PV projects without FIT : Comprehensive techno-economic assessment. *Energy Policy, 146, 111727*. https://doi.org/10.1016/j.enpol.2020.111727

MIŠÍK, M., & NOSKO, A. (2023). Each one for themselves: Exploring the energy security paradox of the European Union. *Energy Research and Social Science*, *99*, 103074. https://doi.org/10.1016/j.erss.2023.103074

MODIGLIANI, F., & MILLER, M. H. (1958). The Cost of Capital, Corporation Finance and the Theory of Investment. *The American Economic Review,* 48(3), 261-297.

MONER-GIRONA, M., KAKOULAKI, G., FALCHETTA, G., WEISS, D. J., & TAYLOR, N. A. (2021). Achieving universal electrification of rural healthcare facilities in sub-Saharan Africa with decentralized renewable energy technologies. *Joule*, *5*(10), 2687–2714. https://doi.org/10.1016/j.joule.2021.09.010

MONER-GIRONA, M., BENDER, A., BECKER, W., BÓDIS, K., SZABÓ, S., KARARACH, A. G., & ANADON, L. D. (2021). A multidimensional high-resolution assessment approach to boost decentralised energy investments in Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews, 148, 111282*. https://doi.org/10.1016/j.rser.2021.111282

MUKORO, V., SHARMINA, M., & GALLEGO-SCHMID, A. (2022). A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value? *Energy Research & Social Science, 88, 102530*. https://doi.org/10.1016/j.erss.2022.102530

MULOPO, J. (2022). A mini-review of practical interventions of renewable energy for climate change in Sub-Saharan Africa in the last decade (2010–2020): implications and perspectives. *Heliyon, 8(11), e11296*. https://doi.org/10.1016/j.heliyon.2022.e11296

OGUNLEYE, O. S., COENEN, F. H., & HOPPE, T. (2022). Stakeholder perspectives on community energy contributing to the use of renewable energy sources and improving energy security in Nigeria. *Energies*, *15*(19), *7390*. https://doi.org/10.3390/en15197390

OLATOREGUN, O., FAGBAMIGBE, A. F., AKINYEMI, O. J., YUSUF, O. B., & BAMGBOYE, E. A. (2014). A comparative analysis of fertility differentials in Ghana and Nigeria. *African journal of reproductive health, 18(3), 36–47*.

ONDRACZEK, J., KOMENDANTOVA, N., & PATT, A. (2015). WACC the dog: The effect of financing costs on the levelized cost of solar PV power. *Renewable Energy*, *75*, 888–898. https://doi.org/10.1016/j.renene.2014.10.053

ORIZU, G. E., OKPALA, U. V., & HUMPHREY, I. (2019). Determination of Number of Days of Autonomy for Battery Sizing in Lagos, Nigeria. *Ife Journal of Science and Technology, 3(1), Article 1*.

OYEWO, A. S., STERL, S., KHALILI, S., & BREYER, C. (2023). Highly renewable energy systems in Africa: Rationale, research, and recommendations. *Joule*, *7*(7), 1437–1470. https://doi.org/10.1016/j.joule.2023.06.004

PASTUKHOVA, M., & WESTPHAL, K. (2020). Governing the Global Energy Transformation. In *Lecture notes in energy*. Berlin, Springer International Publishing. 341–364 https://doi.org/10.1007/978-3-030-39066-2_15

PEDERSEN, M.B. (2016), Deconstructing the concept of renewable energy-based mini-grids for rural electrification in East Africa. *WIREs Energy Environ, 5: 570-587*. https://doi.org/10.1002/wene.205

PEHL, M., ARVESEN, A., HUMPENÖDER, F., POPP, A., HERTWICH, E. G., & LUDERER, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, *2*(12), *939-945*. https://doi.org/10.1038/s41560-017-0032-9

PERKINS-KIRKPATRICK, S. E., & LEWIS, S. C. (2020). Increasing trends in regional heatwaves. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-16970-7

RATEAU, M. (2021). *Configurations électriques, inégalités d'accès et pratiques citadines à Ibadan (Nigéria) et à Cotonou (Bénin)*. Thèse de doctorat. Géographie. Université Paris-Est. Français. ffNNT : 2021PESC2026ff.fftel-03523235f https://theses.hal.science/tel-03523235/document.

REIS, I. F. G., GONÇALVES, I., LOPES, M. A. R., & ANTUNES, C. H. (2021). Business models for energy communities: A review of key issues and trends. *Renewable & Sustainable Energy Reviews*, *144*, 111013. https://doi.org/10.1016/j.rser.2021.111013

RENNERT, K., ERRICKSON, F., PREST, B. C., RENNELS, L., NEWELL, R. G., PIZER, W., KINGDON, C., WINGENROTH, J., COOKE, R., PARTHUM, B., SMITH, D., CROMAR, K., DIAZ, D., MOORE, F. C., MÜLLER, U. K., PLEVIN, R. J., RAFTERY, A. E., ŠEVČÍKOVÁ, H., SHEETS, H., … ANTHOFF, D. (2022). Comprehensive evidence implies a higher social cost of CO_2. *Nature, 610(7933),* Article 7933. https://doi.org/10.1038/s41586-022-05224-9

RICE, I. K., ZHU, H., ZHANG, C., & TAPA, A. R. (2022). A Hybrid Photovoltaic/Diesel System for Off-Grid Applications in Lubumbashi, DR Congo: A HOMER Pro Modeling and Optimization Study. *Sustainability*, *15*(10), 8162. https://doi.org/10.3390/su15108162

SACKEY, C. V.-H., LEVIN, T., & NOCK, D. (2022). Latent demand for electricity in sub-Saharan Africa : A review. *Environmental Research: Infrastructure and Sustainability*, *2*(2), *022002*. https://doi.org/10.1088/2634-4505/ac5fb2

SALMAN, M., LONG, X., WANG, G., & ZHA, D. (2022). Paris climate agreement and global environmental efficiency: New evidence from fuzzy regression discontinuity design. *Energy Policy, 168, 113128*. https://doi.org/10.1016/j.enpol.2022.113128

SAMU, M. FAHRIOGLU AND O. TAYLAN, (2016). Feasibility study of a grid connected hybrid PV-wind power plant in Gwanda, Zimbabwe. *HONET-ICT*, Nicosia, 122-126, doi: 10.1109/HONET.2016.7753434.

SCAPIN, M. (2022). *Exploring Socio-Technical Configurations of Energy Communities: Evaluation, Learnings from Swiss Case Studies*. Université de Genève.

SCHERRER, C. P. (2002). *Genocide and Crisis in Central Africa : Conflict Roots, Mass Violence, and Regional War*. Bloomsbury Academic.

SIMMET, H. R. (2018). "Lighting a dark continent": Imaginaries of energy transition in Senegal. *Energy Research and Social Science*, *40*, 71–81. https://doi.org/10.1016/j.erss.2017.11.022

SIMS, R. E. et al. (2007) In *Climate change 2007: mitigation of climate change*: contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, no. 09. Cambridge University Press.

SOEIRO, S., & AMORIM, M. (2020). Community renewable energy: Benefits and drivers. *Energy Reports, 6, 134–140*. https://doi.org/10.1016/j.egyr.2020.11.087

SOVACOOL, B. K., HOOK, A., MARTISKAINEN, M., BROCK, A., & TURNHEIM, B. (2020). The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. *Global Environmental Change, 60, 102028*. https://doi.org/10.1016/j.gloenvcha.2019.102028

STANDAL, K., LEIREN, M. D., ALONSO, I., AZEVEDO, I., KUDRENICKIS, I., MALEKI-DIZAJI, P., LAES, E., DI NUCCI, M. R., & KRUG, M. (2023). Can renewable energy communities enable a just energy transition? Exploring alignment between stakeholder motivations and needs and EU policy in Latvia, Norway, Portugal and Spain. *Energy Research & Social Science*, *106*, 103326. https://doi.org/10.1016/j.erss.2023.103326

STERL, S. (2021). *Seasons of Power: Streamlining Strategies for Renewable Electricity Generation from Sun, Wind and Water in Sub-Saharan Africa*. Ph.D. thesis. Brussels, Vrije Universiteit Brussel and KU Leuven. http://dx.doi.org/10.13140/RG.2.2.33395.86568/1

STERL, S., SHIRLEY, R., DORTCH, R., MIN, G., & TURNER, A. (2023). A Path Across the Rift: Informing African Energy Transitions by Unearthing Critical Questions and Data Needs. *World Resource Institute, Issue Brief*. https://doi.org/10.46830/wriib.22.00136

TANEJA, J. (2018). If You Build It, Will They Consume? Key Challenges for Universal, Reliable, and Low-Cost Electricity Delivery in Kenya. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3310479

THE 17 GOALS | *Sustainable Development Goals*. (consulted on April 18th). https://sdgs.un.org/goals

TOMC, E., & VASSALLO, A. M. (2016). The effect of individual and communal electricity generation, consumption and storage on urban Community Renewable Energy Networks (CREN): an Australian case study. *International Journal of Sustainable Energy Planning and Management*, *11*, 15–32. https://doi.org/10.5278/ijsepm.2016.11.3

TRISOS, C.H., I.O. ADELEKAN, E. TOTIN, A. AYANLADE, J. EFITRE, A. GEMEDA, K. KALABA, C. LENNARD, C. MASAO, Y. MGAYA, G. NGARUIYA, D. OLAGO, N.P. SIMPSON, AND S. ZAKIELDEEN (2022). Africa. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of United Nations Framework Convention on Climate Change (UNFCCC), China's Achievements, New Goals and New Measures for Nationally Determined Contributions*, UNFCC, Unofficial translation, 2022

TYAGI, A., WARRIOR, D., GANESAN, K., JAIN, R., CHANDHOK, V., DASGUPTA, A., DSOUZA, S., KIM, T.-Y., RAMJI, A., KRISHNAN, D., GUPTA, G., TAGOTRA, N., KUMAR, P., & MANDAL, T. (2023). *Addressing Vulnerabilities in the Supply Chain of Critical Minerals*. https://escholarship.org/uc/item/8m46128h

UN INFO. (2022, October 17) *Afrique de l'Ouest : des inondations déciment des vies et des terres cultivées*. https://news.un.org/fr/story/2022/10/1128902

VAN DEN BRINK, S., KLEIJN, R., TUKKER, A., & HUISMAN, J. (2019). Approaches to responsible sourcing in mineral supply chains. *Resources, Conservation and Recycling*, *145*, 389-398. https://doi.org/10.1016/j.resconrec.2019.02.040

WABUKALA, B. M., MUKISA, N., WATUNDU, S., BERGLAND, O., RUDAHERANWA, N., & ADARAMOLA, M. S. (2023). Impact of household electricity theft and unaffordability on electricity security: A case of Uganda. *Energy Policy*, *173*, 113411. https://doi.org/10.1016/j.enpol.2022.113411

WINTHER, T., MATINGA, M. N., ULSRUD, K., & STANDAL, K. (2017). Women's empowerment through electricity access: scoping study and proposal for a framework of analysis. *Journal of Development Effectiveness, 9(3), 389–417*. https://doi.org/10.1080/19439342.2017.1343368

WORLD BANK. (2020). *Increasing access to electricity in the Democratic Republic of Congo. Opportunities and challenges*. Washington, World Bank.

WU, C.G. , DESHMUKH, R., NDHLUKULA, K., RADOJICIC, T., REILLY. J. (2015). Renewable Energy Zones for the Africa Clean Energy Corridor. https://doi.org/10.13140/RG.2.1.4005.4644.

YAKUBU, O., BABU, C. N., & ADJEI, O. (2018). Electricity theft: Analysis of the underlying contributory factors in Ghana. *Energy Policy*, *123*, 611–618. https://doi.org/10.1016/j.enpol.2018.09.019

YILMAZ, S., RINALDI, A., & PATEL, M. K. (2020). DSM interactions: What is the impact of appliance energy efficiency measures on the demand response (peak load management)? *Energy Policy*, *139*, 111323. https://doi.org/10.1016/j.enpol.2020.111323

Table of Contents