Cape Peninsula University of Technology

# African sustainable energy microgrid development with solar PV and energy storage

**By**

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# DECLARATION

I, Randy Matuka Kabala, declare that the content of this thesis represents my own work and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed Date: 10 July 2023

ABSTRACT
The lack of electricity access presents a considerable barrier to the development of society. That issue is more notable in Africa, precisely in Sub-Saharan Africa where more than fifty percent of the population does not have access to electricity. Multiple studies have shown that much of the African population that lacks electricity access lives in remote areas where there is no grid coverage. The extension of the existing grids to those areas has been deemed a less viable option due to the complexity and high costs associated with that exercise. The identified solution to that problem is the development of a local electrical network, a microgrid, using locally available renewable energy resources such as solar energy to provide electricity access to the surrounding population. The integration of solar PV microgrids is particularly suited for a Sub-Saharan African country such as the Democratic Republic of Congo (DRC) due to their high potential for solar energy and the low cost associated with the technology. Solar PV microgrids also reduce the dependency on fossil fuels and the use of fossil fuel-based power plants which have been proven as major contributors to the detriment of the environment.

This research project developed a microgrid using solar PV to electrify remote communities in the DRC. Given that solar energy is intermittent and is not available during night-time when the electricity demand is usually at its peak, the microgrid was configured with a Battery Energy Storage System (BESS) to ensure an uninterrupted power supply. Also given that the BESS is a high-cost component, the microgrid considered the introduction of a biogas generator, that reduces the BESS architecture which subsequently reduces the cost of the implementation and operation of the system. The microgrid configuration was modelled and simulated using HOMER Pro to determine its techno-economic viability for the electrification of the community compared to the extension of the existing networks.

The simulation results showed that the developed microgrid model using a solar PV, BESS, and biogas generator presented a cost-effective electrical network to electrify remote communities in the DRC compared to the grid extension.

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- My two mothers Beatrice Ngandu and Modestine Ngandu for their spiritual, moral, emotional, and financial support.
- My family, especially my siblings and aunties for their moral and emotional support.
- All my friends for their contributions and support throughout the journey

# DEDICATION

I dedicate this thesis to my Lord and saviour Jesus Christ through whom I have had the strength to complete this project.

I also dedicate this thesis to my mothers Modestine Mbombo Ngandu and Beatrice Mwika Ngandu, who is not able to share this moment with me but I'm convinced that she is watching from heaven where she is in.

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# ABBREVIATIONS/ACRONYMS

| | |
|---|---|
| ANAPI | National Agency of Investment Promotion (Agence Nationale Pour la Promotion des Investissemets) |
| ANSER | National Agency for Rural Electrification Services (Agence Nationale des Services Energétique Ruraux) |
| ARE | Authority for Electricity Regulation (Autorité de Régulation de l'Électricité) |
| DRC | Democratic Republic of Congo |
| ESS | Energy Storage System |
| GW | Gigawatt |
| IPP | Independent Power Producer |
| KW | Kilowatt |
| kWh | Kilowatt-hour |
| MERH | Ministry of Energy and Hydraulic Resources (Ministère de l'Energie et des Ressources Hydrauliques) |
| PAOP | Power Africa Off-grid Program |
| PPA | Power Purchase Agreement |
| PV | Photovoltaic |
| SE4ALL | Sustainable Energy for All |
| SNEL | National Electricity Utility (Société Nationale d'Eléctricité) |
| SSA | Sub-Saharan Africa |
| $ | US$ |

# CHAPTER 1: INTRODUCTION

## 1.1. Problem statement

Sub-Saharan Africa (SSA) has the highest proportion of the population without access to electricity and more than three-quarters of that total population is in rural or remote areas (Africa Energy Outlook, 2022). As part of the SSA region, the Democratic Republic of Congo (DRC) has one of the lowest electricity access rates in the region with more than three-quarters of the population living without access to electricity (ESMAP, 2022). The situation is worse in remote settings where more than 90% of the population lives without electricity (ESMAP, 2022). Although remote areas constitute the majority of the population without electricity access, there is no guarantee of immediate action as the existing network the country relies on is aging, fragmented, and only operates at half of the design capacity (VanderWilde, Fitch and Mueller, 2018). The complexity and high cost associated with the extension of existing networks make it is less viable option hence there is a need for new system development.

## 1.2. Background of the problem

Electricity plays an important role in the socioeconomic development of a country. It is a key contributor to the normal operation of some of the important socio-economical facilities in any nation such as healthcare facilities, schools, and some economic buildings. With the use of renewable energy resources, the negative impact caused by the generation of electricity from fossil fuel power plants has been reduced therefore contributing to the sustainable development goals (Global Commission to End Energy Poverty, 2020).

Despite the considerable potential of the DRC's energy resources, the country still experiences a low electricity access rate and it is considered one of the least electrified counties in the world with more than 80 percent of the population lacking access to electricity (ESMAP, 2022). The percentage varies significantly between urban and rural areas with urban settings having just below 40% access and rural settings having below 1% access (ESMAP, 2022).

The main challenges that characterize the DRC's issue of low electricity access rate are:

**Technical and infrastructural**: Hydro energy constitutes more than 90% of the electricity generation capacity in the DRC. However, the country only utilizes 50% of that generation capacity as hydroelectric power plants do not operate at their full capacity due to the lack of maintenance and aging infrastructures. Inga 1 and 2, which are the largest hydroelectric power plants in the country with a combined generation capacity of 1800 MW from the country's total of 2750 MW, only operate at half their capacity due to the lack of maintenance and falling infrastructures (Stott, 2018)(IRENA, 2021). On top of the underperforming generation plants, the country's transmission networks are also aging and most importantly underdeveloped therefore yielding significant energy losses which ultimately cause inadequacy in electricity services (Energy Systems Research Group, 2020)(Power Africa, 2019).

**Governance**: Until 2014, the state-owned utility company Société Nationale d'Eléctricité (SNEL), had the monopoly of electricity supply in the DRC. However, they were unable to generate sufficient revenue to maintain or expand the existing network which resulted in its inability to provide sustainable electricity to its customers. In 2014 the company was reported to have lost almost $300 million in continuous operational losses (Power Africa, 2019). Given SNEL's inability to provide sustainable electricity, there was an introduction of the electricity law 14-011 of 2014 which aimed to improve the country's electricity sector by liberalizing the production, transmission, and distribution of electricity to the participation of private entities. The introduction of the electricity law ultimately ended SNEL's monopoly. The legislation of the electricity law triggered the creation of Agence Nationale des Services Energétique Ruraux (ANSER) and Autorité de Régulation de l'Électricité (ARE) which are institutions tasked with the responsibility of improving the electricity access of rural and peri-urban areas, and also monitor the electricity sector reform, behaviour of market player and their tariffs. Both institutions were set by decree to operate under the ministry of energy and water resources, however, they are yet to enter into operation (Energy Systems Research Group, 2020)(Quality Infrastructure Investment Partnership, 2019).

Beyond technical and governance challenges, the other factor that contributes to the DRC's low electricity access is the knowledge limitation on the market and data scarcity. Data scarcity creates unpredictability of electricity demand which results in difficulty in planning for electricity supply (The World Bank, 2022) There are limited data on information such as household income, willingness to pay, or payment performance which makes it challenging to determine the market potential (Energy Systems Research Group, 2020). There are also limited data on SNEL's total number of connections which has contributed to the significant rate of illegal connections that negatively affect normal electricity services.

## 1.3. Research questions

The investigative questions used to guide this research project are:

- Will the developed microgrid provide sustainable and affordable electricity to the users?
- What Energy Storage System (ESS) or additional renewable source will be suitable for the microgrid configuration under consideration?
- How will the microgrid system provide sustainable electric energy in the DRC?

## 1.4. Aim and Objectives

This research project aims to develop a microgrid that consists of a solar photovoltaic (PV) source and an Energy Storage System ESS to provide sustainable electricity access in Kongolo which is a town located in the province of Tanganyika in the DRC.

To achieve this aim set for this project, the following objectives were identified:

- Conduct a comprehensive literature review on Solar PV, the ESS, and microgrid technology to determine the most suitable ESS for the system based on the adequate balance of power and cost and the most suitable microgrid system configuration based on the community load requirement.
- Determine the most suitable system location for optimum solar PV penetration using HOMER Pro and/or PVSyst software.
- Determine the most suitable microgrid configuration and size it according to the load requirement using HOMER Pro software.
- Size the renewable energy sources to provide adequate electricity to the users whilst catering to the energy storage system using HOMER Pro software.
- Determine the most suitable ESS and size it according to the load requirement using HOMER Pro software.
- Implement and analyze the operation of the developed microgrid on the HOMER Pro platform.
- Validate the sustainability of the developed microgrid based on the results obtained from the HOMER Pro simulations.

## 1.5. Methodology

To complete the identified objectives, the following steps were carried out:

- A conducted review on solar PV, ESS, and microgrid technology.
  - A comprehensive literature review on solar PV, microgrid technology, and ESS was conducted to get an overview of their operation, configuration, and integration.
  - A literature review was also conducted on the DRC to determine its potential solar PV microgrid integration.

- A site identification was completed using HOMER Pro software. Using the software data on solar radiation, the most suitable location for the microgrid integration was determined.

- Sizing the microgrid to meet the load requirement of the location:
  - An energy demand assessment was conducted on Kongolo to determine the load requirement for the microgrid.
  - The result of the energy demand assessment was used as inputs for the preliminary microgrid configuration and sizing performed on PVsyst.

    - The results of the preliminary sizing on PVSyst were used as inputs to complete the microgrid (including the solar PV and ESS) size on HOMER Pro.

- Computer modeling and simulation of the microgrid:
    - Five different microgrid configurations were completed on HOMER Pro using solar PV, a battery storage system, and an additional biogas generator.
    - The different microgrid configurations were simulated on HOMER and the optimized size of each configuration was selected for comparative studies.

- Validation of the optimized microgrid configuration:
    - The optimization results of the five configurations were compared based on their Net Present Cost (NPC), Cost of Energy (COE), and grid break-even distance.
    - After the comparative studies, the optimized microgrid configuration was furthermore evaluated with reference to external uncertainties namely the availability of renewable resources and increase in load demand.
    - The operation of the microgrid was analyzed and validated to supply the town.

## 1.6. Research delineation

The emphasis of this research project is placed on the techno-economical assessment of the microgrid. It should be able to cater to the load requirement at a more viable cost than the cost of extending the grid.

## 1.7. Thesis outline

This thesis is divided into six chapters. After the introduction, the research is organized in the following way:

**Chapter 2** provides a comprehensive literature review on solar PV, microgrids, and energy storage systems. It also looks at the potential of solar PV resources in the DRC as well as the country's potential for the integration of microgrid systems. The chapter also provides an insight into the work conducted by other research in the implementation of the sustainable microgrid using solar PV and energy storage for rural or remote electrification.

**Chapter 3** provides an overview of different microgrids modeled for the location. Each component is described and their sizes and costs are provided. The chapter also gives an overview of the simulation tools used to complete each system configuration. The energy demand assessment of the location under consideration was also presented in this chapter.

**Chapter 4** presents the simulation results from HOMER Pro in an optimized format. The simulation results were also presented in a form that accounted for uncertainties related to the variation in electricity demand and availability of renewable energy resources.

**Chapter 5** presents a comparative discussion of each configuration's results and then validates the most suitable configuration to meet the load requirement of the location.

**Chapter 6** presents the conclusion drawn from the research project while also presenting some recommendations for future work.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Overview

This chapter looks at the renewable energy resources used to develop the proposed microgrid. It also looks at the key aspects of the microgrid's nature as well as its configuration. The chapter also looks at the energy storage technology used to maximize the use of renewable energy used in the system. The chapter also considers the renewable energy potential of the DRC which is the country under consideration, and the possibility of implementing a renewable energy system based on that potential.

## 2.2. Solar PV technology

Solar Photovoltaic (PV) technology is the process of generating electrical energy using solar radiation. The conversion takes place inside the solar cell which is the basic unit of PV systems. Solar cells consist of two thin layers of different semiconductor materials namely the positive semiconductor (P-type) and the negative semiconductor (N-type). Their principle of operation is that by adding energy, in this case, photons which is the energy carried in sunlight, electrons in the semiconductor get activated and move from the lower energy state to the higher one and so generating electrical energy (Pavlovic, 2020). A solar cell in an electrical circuit is a source of direct current as seen in figure 1.

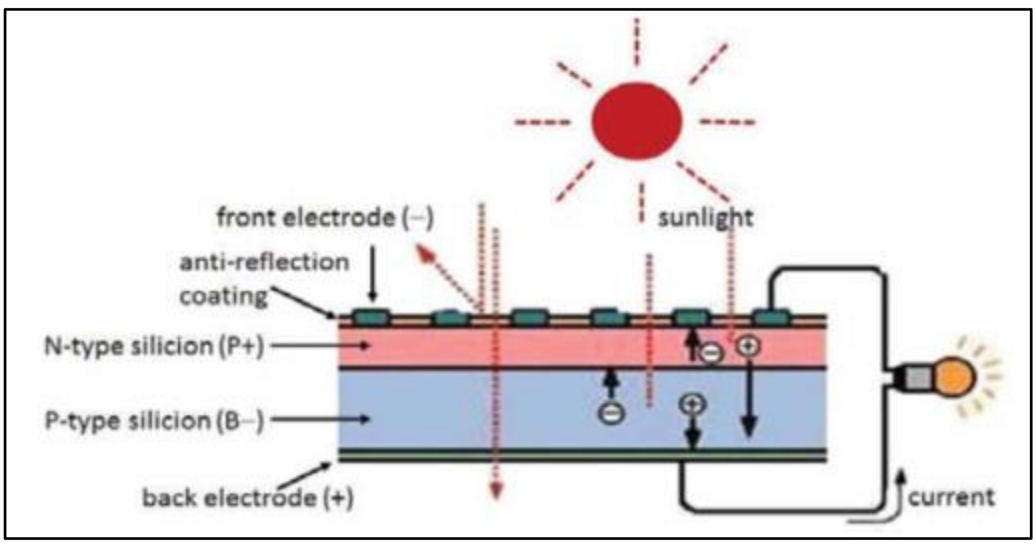


Figure 1: Electrical diagram of a solar cell
(Andjela B, 2021)

Multiple studies have estimated that approximately 90% of solar cells are made from crystalline silicon wafers (c-Si) which contain either single crystals (monocrystalline) or multiple crystals (polycrystalline)(Allouhi *et al.*, 2022). In addition to the silicon crystals, other cells are used to produce solar cells such as thin-film cells in the likes of Cadmium-telluride (CdTe) and Copper Indium-gallium di-selenide (CIGS)(Allouhi *et al.*, 2022). The upcoming paragraphs will briefly elaborate on the different cell technologies and table 1 compares them with regard to efficiency, cost, and performance.

### 2.2.1. Monocrystalline PV cells

Monocrystalline PV cells constitute a single silicon crystal. With a conversation efficiency that can go up to 20%, monocrystalline cells are more efficient than other semiconductors. However, they have a more complex manufacturing process which leads to their costs being slightly higher than the other technologies (Pavlovic, 2020).

### 2.2.2. Polycrystalline PV cells

Also known as multi-crystalline PV cells, polycrystalline PV cells are made of multiple fine silicon crystals. In contrary to monocrystalline cells, polycrystalline cells have a simpler manufacturing process which results in their costs being lower than the ones of monocrystalline. However, the trade-off comes in efficiency as their conversion efficiency is slightly less than the one of the monocrystalline cells (Pavlovic, 2020).

### 2.2.3. Cadmium-telluride (CdTe)

CdTe cells are made from cadmium and tellurium which are both the results of zinc mining and the processing of copper. They are reported to have high efficiency, however, the issue that occurs with their use is the toxicity of cadmium to the environment (Allouhi *et al.*, 2022).

### 2.2.4. Copper Indium-gallium di-selenide (CIGS)

Like cadmium-telluride, these are other thin-film solar cells that are made of a multi-layer of nanocrystalline and a bulk semiconductor absorber layer (Allouhi *et al.*, 2022). These cells achieved an even much higher efficiency than the CdTe and some studies have even favourably compared it with the crystal silicon cells (Kenu E. Sarah, 2020).

Table 1: Comparison summary of different solar PV technologies

| **Properties** | Monocrystalline | Polycrystalline | CdTe and CIGS |
|---|---|---|---|
| **Efficiency** | Highest | Moderate | Lowest |
| **Cost** | Highest | Moderate | Lowest |
| **Performance in High temperature** | Poor | Poor | Better |

## 2.3. Solar PV potential in DRC

Because of their considerable solar penetration, multiple Sub-Saharan African countries, including the DRC, have a significant potential of using solar PV technology to generate electrical energy. They can use technology either on a small scale for local applications or on an electrical system with a decentralized power supply of multiple energy producers and consumers.

DRC receives daily solar irradiation that varies between 2.4 and 6 kWh/m² (Kusakana, 2016). Although the reception varies from one location to another, the majority of the country's surface has a daily reception of at least 3.6 kWh/m² as seen in figure 2, therefore, making the implementation of PV systems feasible in the larger area of the country.

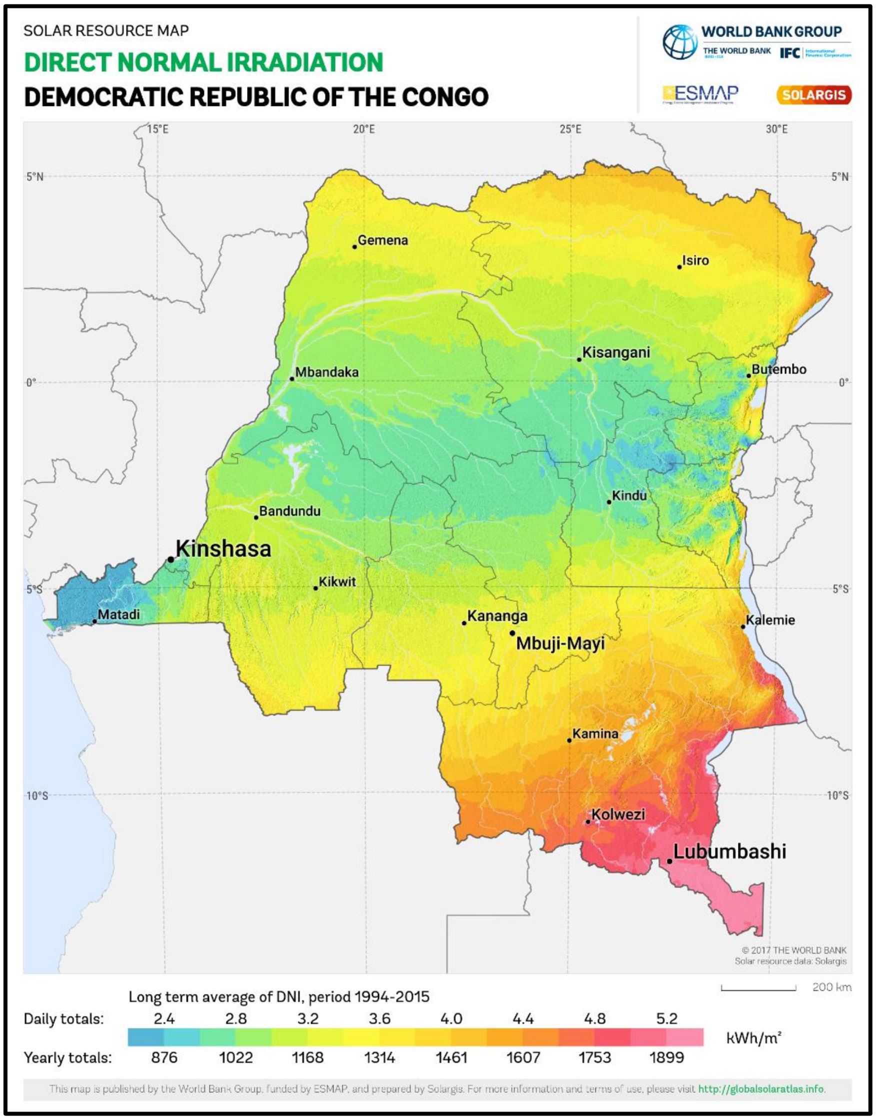


Figure 2: Direct Normal irradiation of the DRC
(SOLARGIS, 2022)

It is worth noting that, despite the country's solar potential, it was reported that DRC only had 83 kW of installed solar countrywide as of 2015 (Stiles and Murove, 2015). However, the effort to tap into the country's PV potential is palpable as IRENA estimated that the country installed solar capacity was 20 MW in 2020 (IRENA, 2021a). Despite all the efforts already made, the country can still significantly improve its solar PV system's capacity as Germany whose PV potential varies between 2.6 and 3.4 kWh/kWp had an installed solar capacity of 53,783 MW in 2020 (IRENA, 2021b).

## 2.4. Microgrid technology

### 2.4.1. Brief overview

A microgrid is an independent and controllable electric power system operating within defined electrical boundaries. It consists of distributed energy resources, load, and energy storage technologies to provide an adequate energy supply to cover the demand. Figure 3 shows a schematic of a microgrid with different connected energy sources. As seen in the figure, some energy sources can be configured as both controllable and non-controllable.

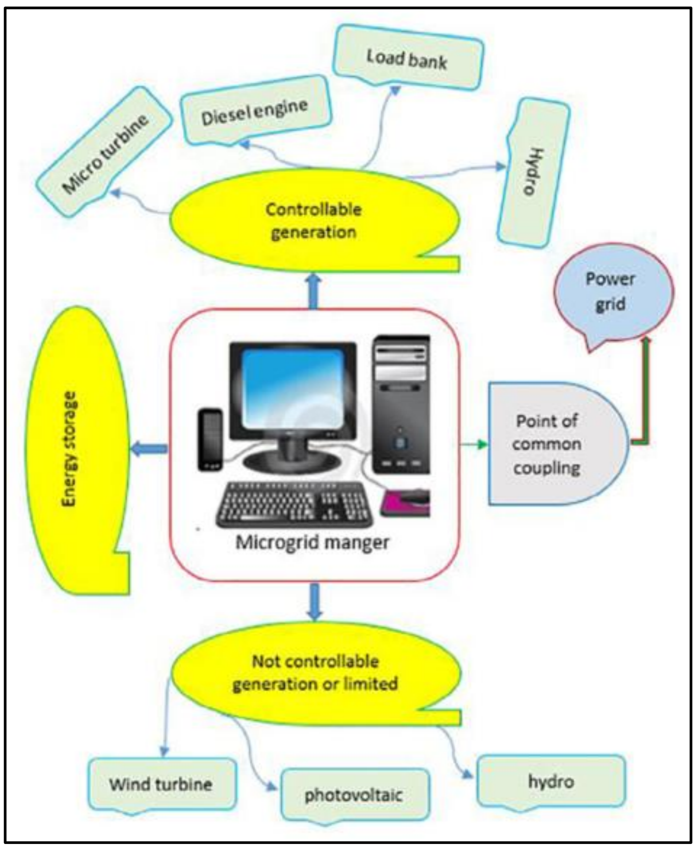


Figure 3: Microgrid schematic with different energy resources
(Shahgholian, 2021)

### 2.4.2. Operations

A microgrid can operate in different modes namely grid-connected, islanded, or standalone, and reconnection mode which allows the increase in reliability of a microgrid by disconnecting it from the main grid in case of a network failure

(Shahgholian, 2021). While operating in grid-connected mode, the microgrid is connected in parallel to an existing grid via the Point of Common Coupling (PCC) for the exchange of power. It can supply its load independently through the import of power from the main grid and can also feed power back to the main grid in a scenario where a renewable energy source, such as solar PV, is used and its total produced power exceeds the load demand at a particular time (Delfino *et al.*, 2018).

While operating in a standalone mode, the microgrid operates independently with independent control to meet the load demand. In this mode of operation, the microgrid is configured with the ability to maintain the power balance indefinitely and use only its energy source, which is generally renewable energy sources, to supply its load (Delfino *et al.*, 2018).

### 2.4.3. Distribution

While looking at power distribution, a microgrid can be classified into three different systems namely an AC system, a DC system, and AC/DC hybrid system. When structured as an AC power system, the microgrid is connected to the distribution network via an AC bus, where all renewable energy sources and loads are also connected as seen in Figure 4. It is worth noting that while the loads are directly connected to the bus, renewable energy sources, as well as energy storage, are connected to the bus via inverters (Delfino *et al.*, 2018).

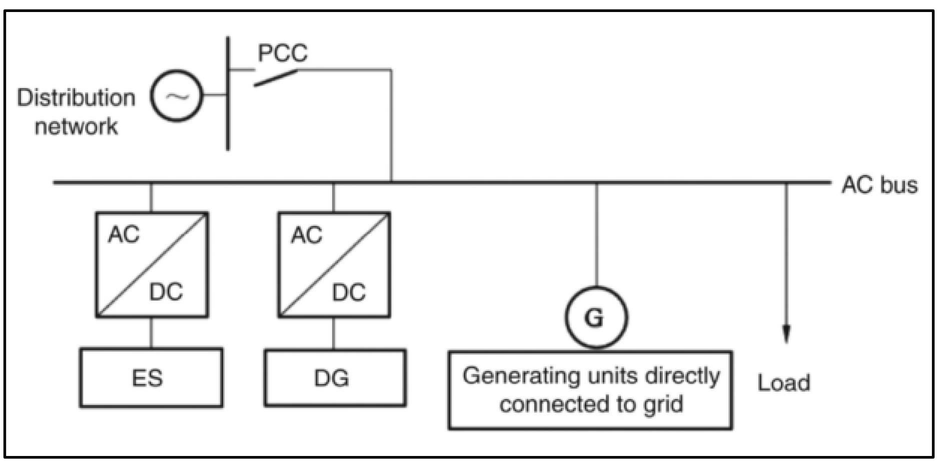


Figure 4: Structure of an AC Microgrid
*(Delfino et al., 2018)*

When structured as a DC power system, all renewable energy sources and DC loads are directly connected to the DC bus, and the AC load is connected to the bus via an inverter as seen in Figure 5 (Delfino *et al.*, 2018).

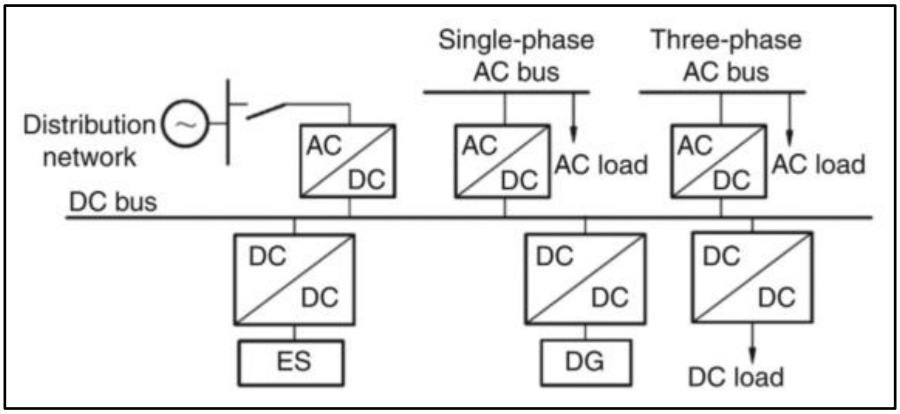


Figure 5: Structure of a DC Microgrid
(Delfino et al., 2018)

For an AC/DC hybrid microgrid, there is a combination of AC and DC buses with each bus allowing a direct connection of either AC and DC load or renewable energy sources as seen in figure 6.

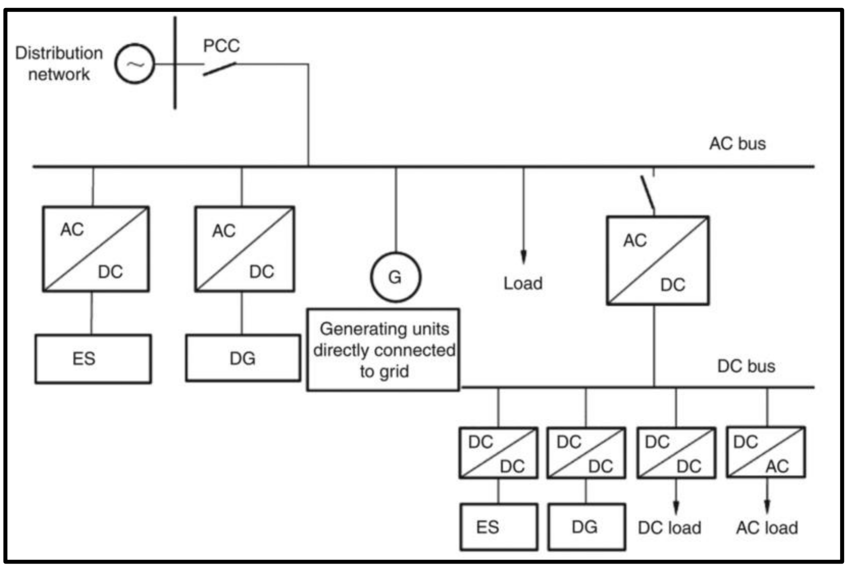


Figure 6: Structure of an AC/DC Hybrid Microgrid
(Delfino et al., 2018)

## 2.5. Microgrids in DRC

### 2.5.1. Overview of the existing grid in the DRC

Before looking at the microgrid status in DRC, it is important to understand the state of the existing grid which is the major cause of the need for microgrids in the country. The current status of grid electrification in the DRC is deplorable making the country one of the least electrified counties in the African continent. For the longest time, DRC has vastly relied on its vast hydro energy resource for electricity generation.  However, despite the country's vast hydro energy potential, reported to be around 100 GW in 2019, DRC only had approximately 2.61 GW of generating capacity in the same year. And of that installed capacity, it was reported that only less than 50% was available for use as most of the country's hydropower plants are older than 50 years old with a lack of proper maintenance (Power Africa, 2019).

DRC is the second largest country in Africa by mass land, with a total of 26 provinces. However, according to the off-grid solar market assessment released by Power Africa Off-grid Program (PAOP) in 2019, it was reported that the country has three regional grids running across six provinces out of the twenty-six (Power Africa, 2019). The coverage of those grids is as follows:

- The Western grid: This grid runs between the province of Kongo Central and the province of Kinshasa.
- The Eastern grid: This grid runs between the North Kivu and South Kivu provinces.
- The Southern grid: This grid covers the province of Haut-Katanga and the province of Lualaba.

There is about 20 % of the population that lives within 15 km of the existing grids, below 40% of the population that lives within the existing and planned grids, and the remaining part of the population is not connected (Power Africa, 2019). Several towns in the other provinces rely on Independent Power Producers (IPPs) for their electricity supply which is an indication of microgrids' opportunities.

In the regions with grid connections, it is only less than 10% of the connected customers are registered by the state utility. Most of the customers are connected informally, and that practice is encouraged by the lack of metering on the customers' end. It is estimated that there are approximately 5 households connected informally for every formal customer causing unreliability in the energy service and lengthy power outages (Power Africa, 2019).

### 2.5.2. Overview of the microgrid in DRC

DRC's limited grid coverage leaves the majority of the population without electricity access and presents significant opportunities for microgrid and/or off-grid systems. Until 2014, the DRC's electricity sector was monopolized by the state-owned utility SNEL. However, since many of the country's electricity concerns were directly linked to SNEL's inability to deliver reliable services, the government decided to end that monopoly by creating the 2014 Electricity Law. Under that law, the government reformed the electricity sector by opening it to private operators and also giving regulatory power to provincial governments (Power Africa, 2019).

After the establishment of the 2014 electricity law, multiple donors such as the World Bank, the African Development Bank, etc. have provided funding to develop the electricity sector. Different IPPs have invested in the development of microgrid and off-grid systems in the different provinces to provide electricity through PPAs. Some of those private power producers are:

1. NURU Energy is a private entity dedicated to enhancing electricity access throughout the country by deploying solar mini-grid and microgrids. The organization which initially started as Kivu Green Energy as it only provided electricity access in the city of Beni, in the North Kivu province, has since changed to NURU which is a Swahili word for "light" to reflect its expansion beyond the Kivu regions (Nuru, 2022).

In 2017, NURU energy installed its first solar PV microgrid with a Battery Energy Storage System to replace the generator-based network which was powering approximately 260 households in the city of Beni. The microgrid consisted of 55 kWp of solar PV and 109 kWh of storage capacity (Jackson, 2018). After the successful implementation of its first microgrid, the organization vowed to roll out similar systems to reach 10 MW of solar PV plus battery energy storage systems by the year 2030 (Jackson, 2018).
In 2018, NURU energy conducted a study to determine the feasibility of implementing an hybrid microgrid to supply a farming area in the city of Beni. The area consisted of approximately 500 households and was mainly supplied with diesel generators. The main objective of the study was to determine if the hybrid microgrid could provide a lower cost of energy in comparison to the cost of energy paid on the generator-based system and the results of the study showed that an hybrid microgrid consisting of 238 kWp of solar PV, 380 kW of biogas generator and 690 kWh of battery energy storage could supply the community with a cost of energy of 0.37 $/kWh compared to the 0.73 $/kWh paid on the generator-based system (Vander Wilde, Fitch and Mueller, 2018).
In 2020 NURU energy inaugurated a solar PV microgrid which consists of 1.3 MW of solar PV and battery energy storage in the city of Goma to electrify approximately 750 households (NURU Energy, 2020). The commissioning of this system represented a considerable step to the organization's aim of reaching 10 MW of solar microgrids by 2030.

2. Electricity of Congo (Eléctricité du Congo [EDC]) provides electricity to thousands of customers in Tshikapa, in the Kasai province (Power Africa, 2019).

3. Kasai Energy Company (Société d'Energie du Kasai [ENERKA]) provides electricity access to the Kananga region in the Kasai central province through the grid-

connected network facilitating the extension of the SNEL network in the region (Power Africa, 2019).

The establishment of the electricity law has also paved the way for different studies to determine the feasibility of using renewable energy microgrids as standalone systems to improve the electricity rate of the country. A study conducted by (Josue and Mushi, 2022) showed the ability of renewable microgrids to electrify both rural and urban areas in the DRC using locally available resources. The study looked at three renewable energy resources namely solar, hydro energy, and biomass resources in the form of municipal solid waste. The results of the study showed that:

- There are at least 10 cities in the country that can be powered with standalone microgrids using municipal solid waste with a combined generation capacity of 83,790 kW. Amongst those cities, Kinshasa has the largest potential of 50,000 kW and Likasi has the smallest potential of 1,686 kW.
- There are at least 25 cities that can be electrified using hydroelectric microgrids with a combined capacity of 50,900 kW. The city of Mbandaka, Aru, Feshi, and Mwene-Ditu have the largest potential of 5,000 MW each and the city of Nonda has the smallest potential of 300 kW.
- There is a potential of 661,000 kW solar PV microgrids spread across a minimum of 8 cities namely Kinshasa, Kikwit, Mbuji-Mayi, Lubumbashi, Mbandaka, Kindu, Kasongo, and Kananga.

While renewable microgrid studies in the DRC generally focus on their abilities to electrify rural areas, some studies look at how they can be operated in a grid-connected mode to improve the performance of the existing grid. (Ecike, 2019) showed that solar PV microgrids with battery energy storage can be used to improve the reliability of the grid in major cities such as Kinshasa, where there is frequent load shedding, by reducing the unavailability of electric current in the network.

### 2.5.3. Government policy on microgrids

An enabling public policy environment is critical to the success of electrification-based microgrids as they promote the necessary rules, regulations, and procedures to usher the microgrid deployment and operation in particular for rural and remote applications (AUDA-NEPAD, 2018). In the DRC, the institutional setting is complex, as multiple parties are involved. The 2014 Energy Law transferred responsibilities to the provincial government as well, therefore, involving both parties, the central and provincial governments, and both being overseen by the MERH. The law looks at different energy activities such as production, distribution, import, export, and commercialization. It also mandated the creation of ARE and ANSER. The creation of all those parties necessitates the involvement of multiple agencies during planning, therefore leading to complexity.

Nevertheless, the 2014 Law has led to the private sector operating in the energy sector in the country (African Development Bank, 2017).

The summary of DRC's microgrid policy and regulatory environment is as follows:

- **Licensing:** the 2014 electricity law's main purpose was to promote private investment in generation and distribution across the DR. However, it requires the power distributor of any scale operating in the public domain to obtain a concession, which will last at least 30 years, through a tender process coordinated by ARE. For the majority of the project, the authority to grant the concession is vested in the provincial government (African Development Bank, 2017).

- **Tariff**: Microgrid operators can propose tariffs that guarantee the return on their investment while developers can provide tariffs that reflect the true cost of structure incurred by the operators based on the rules and guidelines deployed by the regulators. Those tariffs must also be approved by the MERH and the Ministry of Economy after the regulator's review (African Development Bank, 2017).

- **Technical rules:** All microgrid projects must follow the country's general specifications for electricity projects and the installation must conform with the country's general technical norms and standards used (African Development Bank, 2017).

- **Grid arrival:** The 2014 electricity law does not take into consideration cases where the installed microgrid is reached by the main grid. Although the concession contract goes up to 30 years, giving some security to the operator, and the lack of investment in the transmission network reduces that possibility, it still does not eliminate it. Future: look into the grid connection.

## 2.6. Energy storage technologies

The energy produced by renewable energy sources is sporadic. In the case of solar energy, there is generally a gap between the time of energy demand and resource availability. The energy produced by solar energy cannot be used at night-time, therefore it is necessary to store the energy produced during the day for later use. There are several technologies used to store electrical energy, e.g. electrochemical, mechanical, and chemical technology. Figure 7 shows some technologies and a few types of storage per technology.

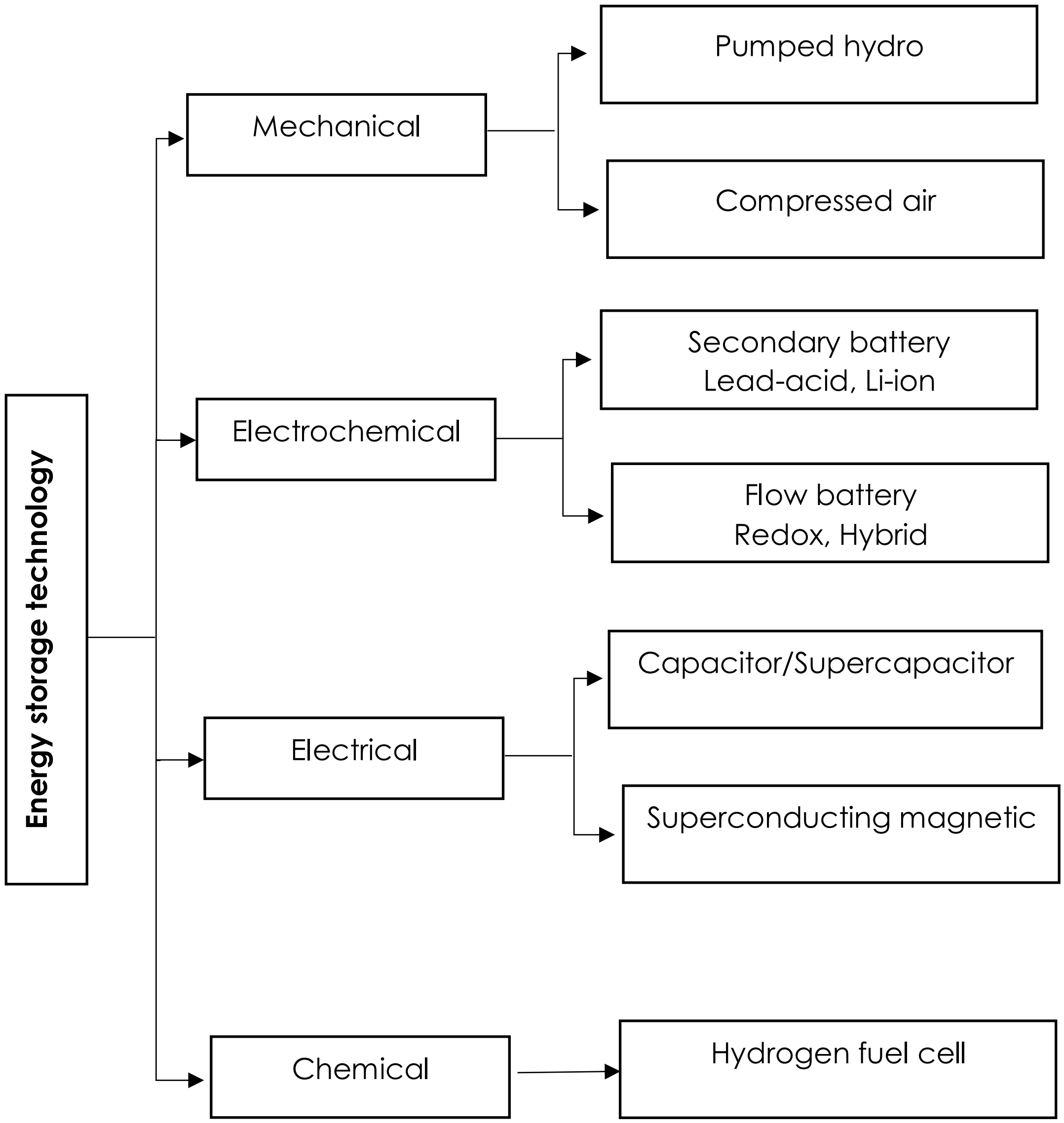


Figure 7: Classification of energy storage technologies
(Hossain *et al.*, 2020)

### 2.6.1. Mechanical energy storage

Mechanical storage technology is based on the conversion of kinetic energy into electric energy using physical movements. The most common types of mechanical energy storage are pumped-hydro and compressed air energy storage.

**(1) Pumped-hydro storage (PHS)**

The pumped-hydro storage is an adjustment of the conventional hydroelectric power plant operation. The system is configured with two reservoirs, one above the other and it is also fitted with a turbine as seen in figure 8. When in operation, water is pumped to the upper reservoir during times of low peak demand and then released to the lower reservoir during times of high peak demand. When released to the lower reservoir, the discharged water drives the generator to produce electrical power (Hossain *et al.*, 2020).

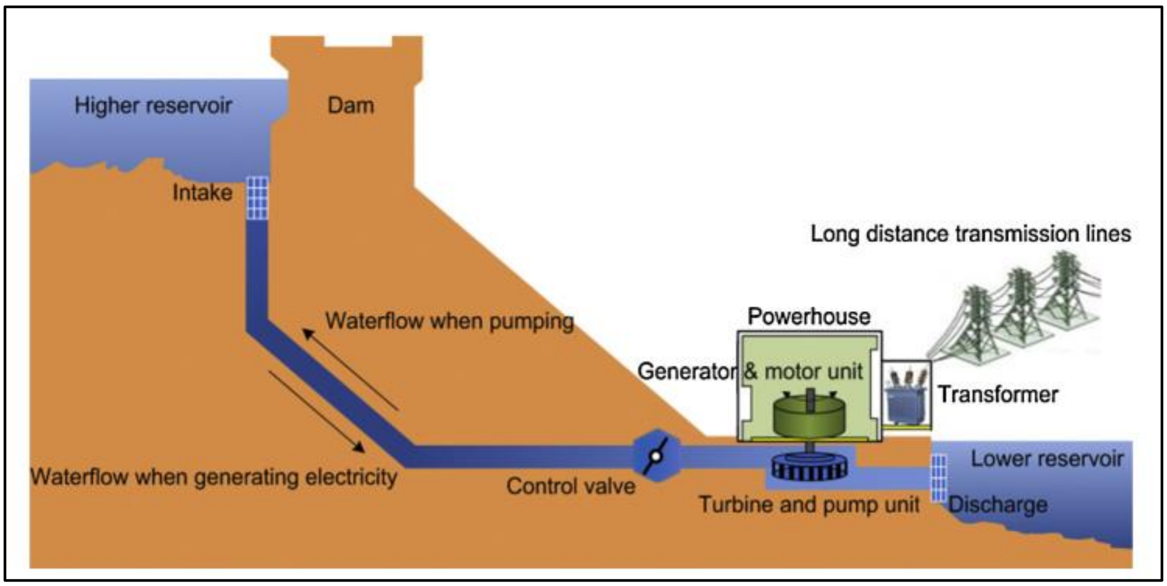


Figure 8: Layout of a pumped hydroelectric storage plant
(Luo et al., 2015)

**(2) Compressed air energy storage (CAES)**

In compressed air energy storage, electrical energy is stored by compressing or pressurizing air into a vessel. The system is configured with a storage vessel and a compressor or expander as shown in figure 9. The operation of the compressed air storage is like the one of the pumped-hydro storage; during low peak demand, the air is compressed at high pressure and stored in the vessel. The compressed air is then released during high peak demand. The energy is released by expanding the air through the expander. Together with PHS, CAES is the only large-scale energy storage system, however, when comparing the two of them, CAES are in smaller sizes (Hossain *et al.*, 2020).

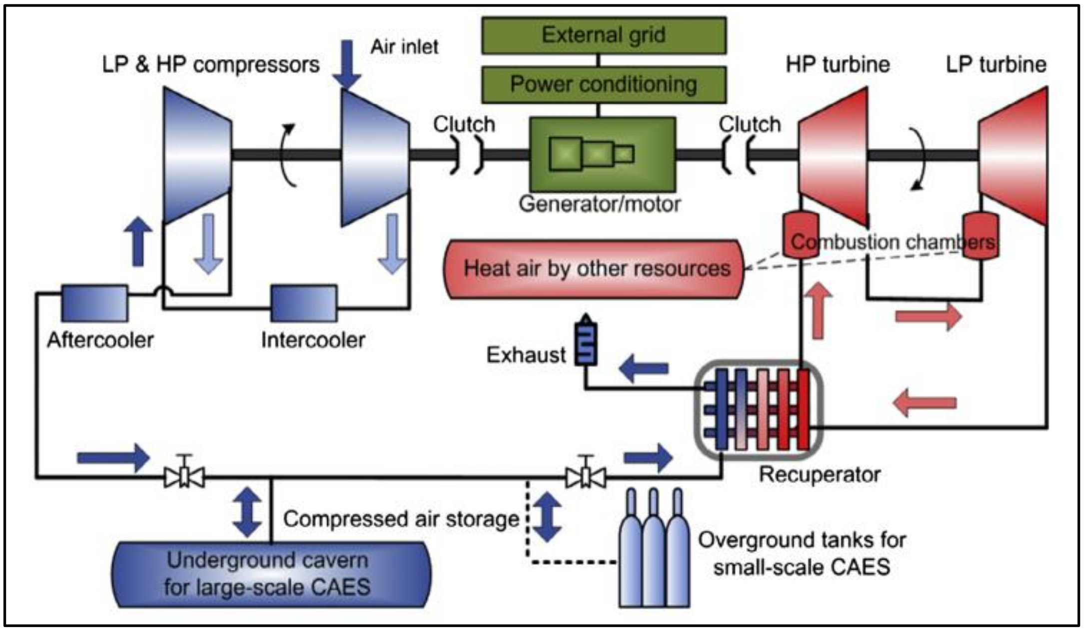


Figure 9: Schematic diagram of a CAES facility
(Luo *et al.*, 2015)

### 2.6.2. Electrochemical energy storage

Electrochemical energy storage is used as a reference to the storage of energy using batteries (Hossain *et al.*, 2020). When a potential voltage is applied to the electrodes (anode and cathode), there is a chemical reaction that takes place inside a battery, therefore, charging it. When the potential energy is removed, a reverse reaction takes place, therefore, discharging the battery. Figure 10 shows a schematic diagram of the operation of the battery energy storage system.

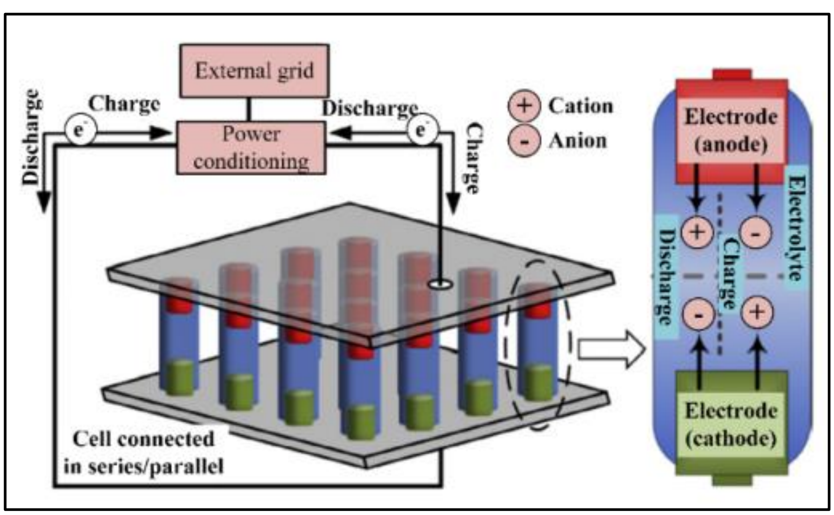

Figure 10: Schematic diagram of the battery energy storage system operation (Hossain *et al.*, 2020)

Depending on the chemistry and construction, batteries are mostly categorized as lead-acid, Lithium-ion (Li-ion), sodium-sulfur (NaS), and flow batteries.

**(1) Lead-acid batteries**

Lead-acid batteries are based on the electrochemical reaction between the positive electrode which contains load dioxide ($PbO_2$) and the negative electrode which contains sponge lead (Pb) (Hossain *et al.*, 2020). They are mainly used for renewable energy systems to provide back-up or uninterrupted power. They are easy to carry and have a low cost. However, the trade-in with these types of batteries is that they have a lower life cycle, low depth of discharge, and shorter lifetime (Hossain *et al.*, 2020).

**(2) Lithium-ion (Li-Ion) batteries**

Li-Ion batteries are based on the exchange of lithium particles from the anode to the cathode while charging and the other way around to discharge. There are generally used in electronic devices e.g. cell phones and laptops due to their long life cycle, high voltage operation, higher depth of discharge, and higher density. The trade-in with all the advantages they come with is that Li-Ion batteries have a high cost (Hossain *et al.*, 2020).

**(3) Sodium-sulphur (NaS) batteries**

Sodium-sulfur batteries are configured in a way that sodium is the cathode and sulfur is the anode. The positive particles travel through the batteries and join the sulfur to make up the sodium polysulfide. The Sodium-sulphur also has a high density, long cycle life, and comes at a cheaper cost. These types of batteries can operate at higher temperatures (Hossain *et al.*, 2020).

### 2.6.3. Electrical energy storage

Capacitors/supercapacitors and superconductor magnets can be used to store energy in an electric form.

**(1) Capacitor/Supercapacitors**

In a capacitor, energy is stored using two conductive metal plates that are separated with a medium. By applying a voltage across the conductive plates, there is an electric charge that is stored. Capacitors have a long lifecycle and instantaneous recharging capabilities, however, their low energy density limits their applications to low-scale power control systems. To overcome capacitors' limitations, supercapacitors were introduced. They have a higher power density, increased lifecycle, and higher output power (Hossain *et al.*, 2020).

**(2) Superconducting magnetic energy storage (SMES)**

The SMES stores energy using a magnetic field created by the flow of direct current in the coil (Hossain *et al.*, 2020).

### 2.6.4. Chemical energy storage

Chemical storage uses the chemical reaction of the chemical bonds of molecules to produce energy. The endothermic reactions require energy to build the bond in a high-energy product while the exothermic reaction release that energy. One of the most common types of chemical energy storage is hydrogen fuel cells. A fuel cell is a cell that can directly produce electrical energy using the chemical reaction of chemical energy. Hydrogen is the cell with the highest energy per mass (Hossain *et al.*, 2020).

## 2.7. Previous studies on solar PV microgrid and energy storage

Multiple studies have been conducted to confirm the ability of renewable energy microgrids to electrify remote and rural locations. While some of those studies only focused on the microgrid feasibilities, others looked at their techno-economic advantages compared to grid extension. A study conducted by (Mulenga *et al.*, 2023) shows the techno-economic viability of a solar PV microgrid plus a diesel generator and battery energy storage to electrify remote areas in Zambia. The study used HOMER Pro to complete the system modeling and determine the most suitable system configuration. Multiple configurations were considered and the results of the study showed that configuring the microgrid with a single power supply was not an economically viable option. A stand-alone microgrid with a diesel generator had the highest COE despite its lowest capital cost. A stand-alone microgrid with solar PV and battery energy storage presented an economically viable option for the lifetime of the project, however, its initial cost was higher. To compensate for that high capital expenditure (CAPEX) cost, a diesel generator was integrated into the system making it a more suitable microgrid configuration.

A study conducted by (Rousis *et al.*, 2018) presented the design of an autonomous AC/DC microgrid to electrify a few residential settlements on an island with no possibility of grid access. HOMER Pro was used to identify the least-cost design option to cater to the load requirement with an uninterrupted power supply. To determine the most optimum system configuration, all possible design choices presented by the software were analyzed and another key performance indicator considered in the analysis was the carbon emission of the system to ensure that the microgrid under consideration does not present environmental disadvantages. The results of the study concluded that a hybrid microgrid consisting of solar PV, diesel generator, and lead-acid batteries presented the most cost-effective and environmentally friendly configuration. The study also conducted a sensitivity study which showed that the diesel generator fuel cost and solar PV size are proportional meaning that as the diesel fuel cost increases, there is a need for an increase in solar PV capacity.

Using HOMER Pro, (Muskan and Kaur Channi, 2023) conducted an investigative study to determine the feasibility of a solar PV-diesel generator microgrid to electrify a remote district in India to reduce the dependence on grid power. The results of the study showed that a hybrid microgrid with solar PV and diesel generator presents a suitable configuration for the electrification of microscale villages and reduces the use and dependence on fossil fuel generation. To determine the most optimum system configuration, the study also analyzed all the possible design configurations generated by the software.

A study conducted by (Mulenga *et al.*, 2023) showed that configuring a microgrid with solar PV and battery energy storage required a higher starting cost but that cost could be reduced with the integration of a diesel generator to the configuration. A study conducted by (V. and Verma, 2021) used mixed integer linear programming in an attempt to find the optimal solar PV and battery storage sizes that eliminates the need for diesel generator. The result of the study showed that to reduce the initial cost of the microgrid using solar PV and battery energy storage only, a grid connection is necessary, however for an isolated microgrid an addition source such as a generator provides the most optimum configuration.

A study conducted by (Riayatsyah *et al.*, 2022) investigated the possibility of either replacing existing diesel generators or integrating a renewable energy microgrid as a supplement to the generators to electrify an island. HOMER Pro was used for the optimum system analysis and the results of the study showed that integrating solar PV and battery energy storage with the existing generators on-site presented the most suitable techno-economic microgrid configuration for the island compared to replacing the existing generator. Those results also proved that a solar PV microgrid with battery storage can have its system cost reduced by integrating a generator into the system architecture.

# Chap 3: System modelling and design

## 3.1. Overview

This chapter presents the microgrid model designed to address the identified problem. It presents all microgrid configurations identified to meet the electricity requirement of the community. The chapter also gives a brief site description of the location and its background. It also provides a short energy resource assessment and looks at the energy requirement which is the load to be catered for by the microgrid. The chapter also presents a quick overview of the software used to model the microgrid.

## 3.2. System description and configuration

The main scope of this study was to develop and propose a microgrid that consists of solar PV and an energy storage system to electrify the population of Kongolo in the province of Tanganyika. According to the DRC solar market assessment performed by PAOP, more than 90 % of households in the province of Tanganyika were located beyond 10 km of the existing High Voltage networks as of 2019 (Power Africa, 2019). Reports from the World Bank highlighting the opportunities and challenges of increasing electricity access in the DRC showed that Kongolo was a viable candidate for an isolated microgrid as it was located over 20 km away from the nearest existing grid connection (The world bank, 2020). Taking into consideration the distance between Tanganyika and the existing networks, ANSER mainly planned to electrify the province with solar systems on the horizon of 2030 as they can be developed closer to the location they are going to supply and do not require a connection to the existing grid (ANSER, 2022).

The microgrid designed in this study was an AC-coupled microgrid as shown in figure 11. It is a completely off-grid system consisting of solar PV, battery energy storage, and a biogas generator (Biogen). Five different configurations were extracted from this model and simulations were performed on HOMER Pro to determine the most suitable system configuration for the province in terms of cost and sustainability.

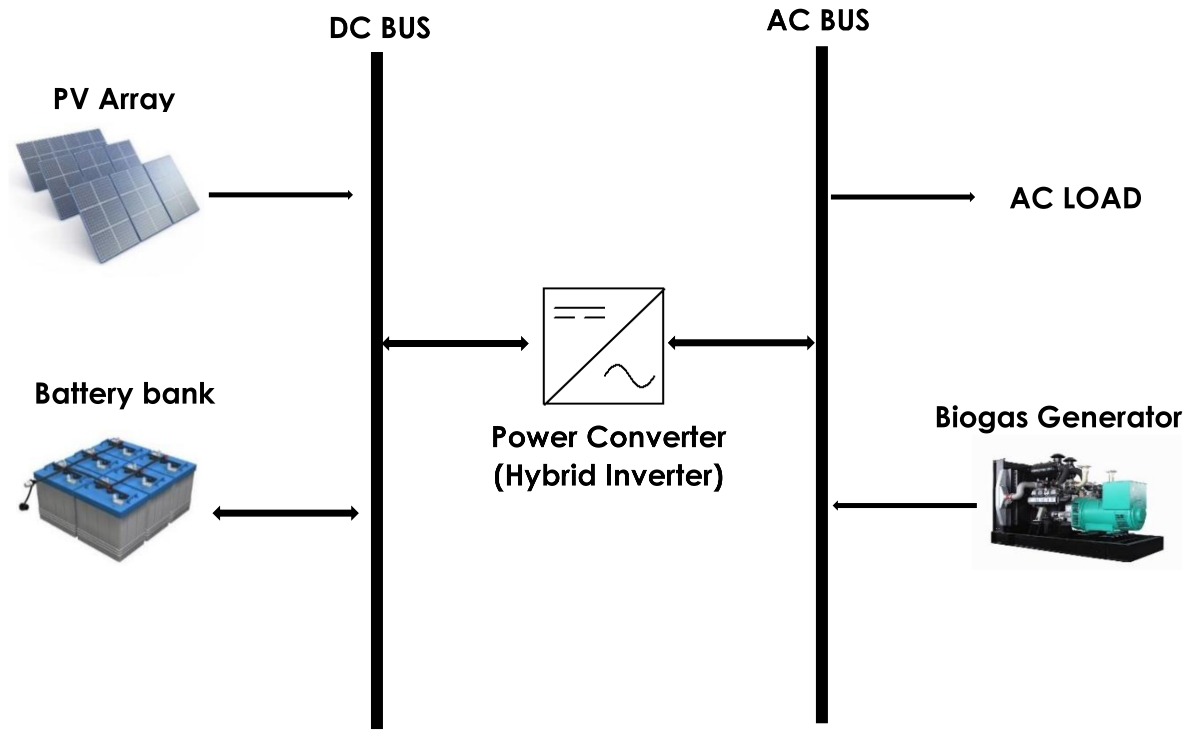


Figure 11: Standalone AC-coupled microgrid configuration

The five system configuration considered to supply the community were:

- Configuration 1: System consisting of solar PV only
- Configuration 2: System consisting of biogas generator only
- Configuration 3: System consisting of solar PV and biogas generator
- Configuration 4: System consisting of solar PV and BESS (Battery Energy Storage System)
- Configuration 5: System consisting of solar PV, BESS, and Biogas generator

The next sections will provide details on each system component.

### 3.2.1. Configuration 1 – Microgrid with solar PV

In this configuration, there were two main components in the system which were the solar PV and the hybrid inverter as shown in figure 12.

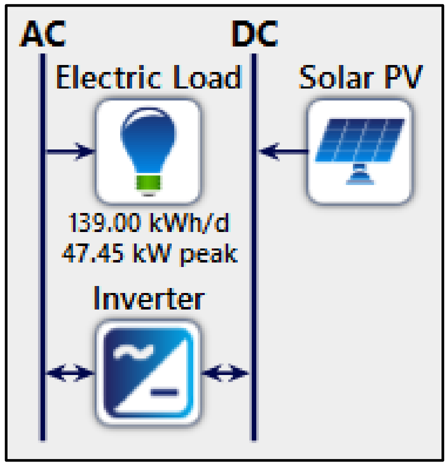

Figure 12: Microgrid configuration with solar PV only

### 3.2.2. Configuration 2 – Microgrid with biogas generator

This configuration consisted of the biogas generator only. It was supplying the load directing via the AC bus and there was no requirement for the power converter equipment. Figure 13 shows the microgrid configuration as developed in HOMER Pro.

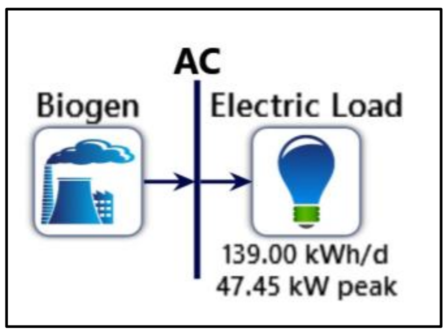

Figure 13: Microgrid configuration with biogas generator only

### 3.2.3. Configuration 3 – Microgrid with solar PV and biogas generator

In this configuration, there were three main components in the system which were the solar PV, the biogas generator, and the hybrid inverter as shown in figure 14.

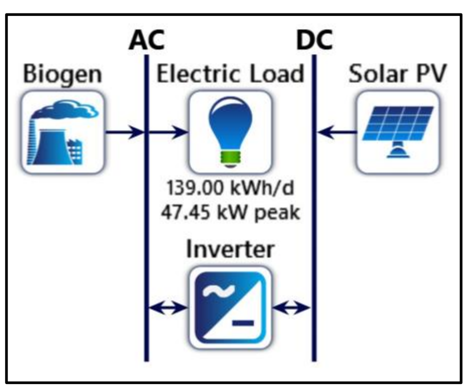

Figure 14: Microgrid configuration with Solar PV and biogas generator

### 3.2.4. Configuration 4 – Microgrid with solar PV and BESS

In this configuration, there were also three main components in the system which were the solar PV, the battery pack, and the hybrid inverter as shown in figure 15.

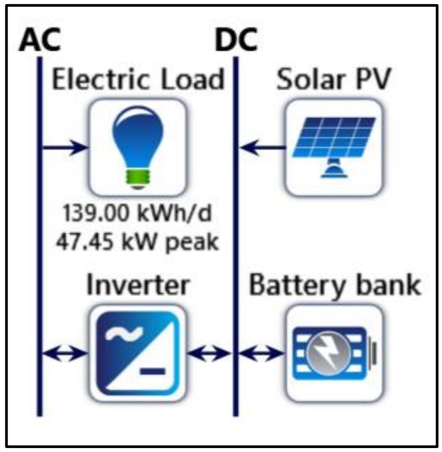


Figure 15: Microgrid configuration with solar PV and battery energy storage

### 3.2.5. Configuration 5 – Microgrid with solar PV, BESS and biogas generator

In this configuration, there were four main components in the system which were the solar PV, the battery pack, the biogas generator, and the hybrid inverter. Figure 16 shows the microgrid configuration as developed in HOMER Pro

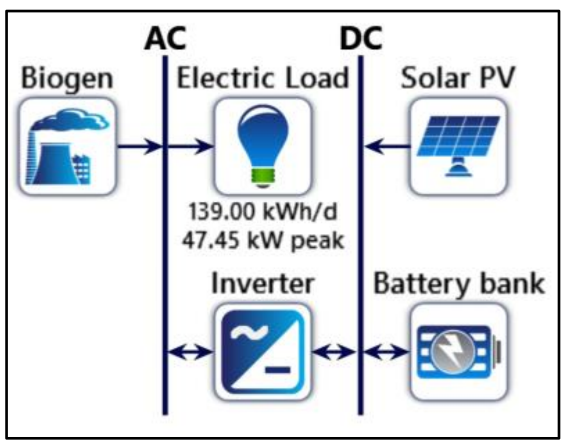


Figure 16: Microgrid configuration with solar PV, battery energy storage and biogas generator

## 3.3. Component sizing

While designing a renewable energy-based system, an optimal sizing of the system is an essential step to providing a reliable power system as oversizing of the system will not only lead to power loss but also to overcharging the system users while under-sizing may lead to unreliability of the system. The next sections will detail each component used in the system.

### 3.3.1. Solar PV modules

The cost of solar PV panels has decreased significantly in the past couple of years and it is assumed to continue its downslope in the upcoming years due to the growing influence of the technology in the development of renewable energy systems (IRENA, 2020). The cost of a solar PV system is made up of multiple factors such as the size of the system, its location, and other additional component required for its installation such as the switchgear, installation cables, and mounting structures (Odoi-Yorke *et al.*, 2022). In the context of the DRC, the government of the DRC has removed certain costs such as the import duties and Value-Added Tax (VAT) on renewable energy generation equipment, tools, and spare parts to facilitate the development of renewable energy systems in the country (Power Africa, 2019).

After a preliminary simulation on PVSyst, the solar PV capacity to supply the community was expected to be approximately 40 kW. Based on the preliminary results, two more solar PV sizes were configured as inputs while simulating in HOMER to allow for the selection of the most suitable size. The capital cost of the PV system was taken as 2 $/W with reference to a project conducted by NURU (VanderWilde, Fitch and Mueller, 2018) in a similar set-up. The replacement cost was taken as a quarter of the capital cost and maintenance cost was not considered as solar systems have static components that require little maintenance. Table 2 shows the different system sizes considered in this study as well as their techno-economic inputs in HOMER Pro software.

Table 2: Solar PV configuration inputs to HOMER Pro

| PV capacity (kW) | Capital cost ($) | Replacement cost ($) | Lifetime (Years) |
|---|---|---|---|
| 25 | 50,000 | 12,500 | 25 |
| 40 | 80,000 | 20,000 | 25 |
| 55 | 110,000 | 27,500 | 25 |

### 3.3.2. Biogas generator

A biogas system consists of a biodigester that converts raw biomass feedstock into biogas through anaerobic digestion and a generator that uses the produced biogas to generate electrical energy (The World Bank, 2022). Although the cost of a biogas system mainly includes the cost of a biodigester and the generator, other factors influence its cost such as the piping and cleaning component (Odoi-Yorke *et al.*, 2022). It is not clear if the established tax exemption on renewable energy components in DRC also applies to the import of biogas generators. However, should that not be applied to the generators, there is a general investment code through the ANAPI allowing renewable energy organizations or projects to benefit from tax and duty exonerations (Power Africa, 2019).

Three different size configurations of biomass generators were considered for the HOMER Pro simulation. The capital costs of the generator were taken as 500 $/kW as estimated by the National Renewable Energy Laboratory (NREL) for typical biogas generator installation (Schroeder and Joelynn, 2022). The Replacement cost was assumed to be the same as the capital cost and the maintenance cost at 0.5 $/hour. Table 3 shows the different generator sizes considered in this study as well as their techno-economic inputs in HOMER Pro software. The generator sizes was taken based on standard off-the-shelf equipment.

Table 3: Biogas generator configuration inputs to HOMER Pro

| **Generator capacity (kW)** | **Capital cost ($)** | **Replacement cost ($)** | **O&M cost ($/hour)** | **Lifetime (Years)** |
|---|---|---|---|---|
| 13 | 6,500 | 6,500 | 0.5 | 25 |
| 20 | 10,000 | 10,000 | 0.5 | 25 |
| 25 | 12,500 | 12,500 | 0.5 | 25 |

### 3.3.3. Battery

In any renewable energy system where batteries are used, their costs usually make up the biggest portion of the total system cost. The cost of battery energy storage consists of different factors such as the battery technology, and the cost rate of the system based on its energy capacity and its power capacity. As indicated earlier, battery modules, which form part of the renewable energy equipment, also benefit from the tax exemption while being imported into the DRC. The exemption of VAT or tax exonerations on battery modules is a much-needed operation as they generally carry some of the biggest costs in renewable energy systems. After the preliminary system design using PVSyst, the expected system's required battery energy storage was 290 kWh. However, to determine the most suitable system configuration, three different battery storage configurations were input to HOMER Pro. The batteries considered in this study are Li-ion batteries with a capital cost of $30,000 for 100 kWh. The replacement cost was taken as half of the capital cost and a maintenance cost was taken as 100 $/year. The cost was also taken from a conducted project by NURU (Vander Wilde, Fitch and Mueller, 2018). The different battery configurations considered in this study are shown in table 4 as well as their techno-economic inputs in HOMER Pro.

Table 4: Battery configuration inputs to HOMER Pro

| **Storage capacity (kWh)** | **Capital cost ($)** | **Replacement cost ($)** | **O&M cost ($/hour)** | **Lifetime (Years)** |
|---|---|---|---|---|
| 100 | 30,000 | 15,000 | 100 | 10 |
| 200 | 60,000 | 30,000 | 100 | 10 |
| 300 | 90,000 | 45,000 | 100 | 10 |

### 3.3.4. Inverter

For any system consisting of both AC and DC, an inverter is required to convert the DC power into AC, and a rectifier to convert AC power into DC. Hybrid inverters are commonly used types of inverters and as their names suggest, they can operate in two different directions, inverters as well as rectifiers. The total cost of an inverter includes the unit price plus the local tax and shipping cost. However, as a tool for renewable energy equipment, it was assumed to also benefit from a tax exemption leaving its total cost only with the unit price. Unlike the other component configuration in the system, the converter was only taken in one size with a capital and replacement cost of $7300 as shown in table 5.

Table 5: Converter configuration inputs to HOMER Pro

| **Input** | **Description** |
|---|---|
| Inverter Nominal capacity (kW) | 30 |
| Capital cost ($) | 7,000 |
| Replacement cost ($) | 7,300 |
| O&M cost ($) | 100 |
| Lifetime (Years) | 10 |

### 3.3.5. Economic input

This study aims to find the optimal system configuration at the least cost. Economic inputs play an important role in the simulation of the system as they ultimately influence the cost of the system. The economic parameter of the system in consideration in this study is presented in table 6. It is worth noting that there was an initial 12% discount rate that was input for the system, however using the sensitivity analysis, the rate was scaled up in steps.

Table 6: System economic inputs to HOMER Pro

| **Input** | **Description** |
|---|---|
| Discount rate (%) | 12 |
| Inflation rate (%) | 7 |
| Annual capacity shortage (%) | 0 |
| Project lifetime (Years) | 25 |

### 3.3.6. Sensitivity analysis

When designing a renewable energy system with a renewable energy source such as solar, it is important to consider the uncertainty associated with their resources. It is also important to consider the increase in load requirement as the availability of electricity leads to more electrical appliances being procured or more people wanting to be connected to the system, in other words, the availability of electricity leads to the increase in demand. The increase in demand leads to variation in the system's operation, a situation that can be accounted for in the sensitivity analysis. The sensitivity analysis allows the designer to create a practical design that takes into consideration all the changes mentioned above.

In this study, the selected initial parameters whose uncertainty had to be covered by the sensitivity analysis were the discount rate, the increase in electricity demand, and the availability of biomass feedstock as shown in table 7.

Table 7: Sensitivity analysis inputs for HOMER Pro simulation

| Input | Description |
|---|---|
| Discount rate (%) | 12, 15, 18 |
| Increase in electricity demand (%) | +25, +50, +75, +100 |
| Availability of biomass (Average in t/year) | 29, 19, 9 |

## 3.4. Load demand assessment

### 3.4.1. Background of the location

The city of Kongolo is a town in the province of Tanganyika in the DRC. Like Haut-Lomami, Lualaba, and Haut-Katanga, the province of Tanganyika is a result of the dismemberment of the previous province of Katanga. As of 2021, the city had a total population size of 605,849 inhabitants, and according to ANSER, only 16% of the total population had access to electricity in the same year (ANSER, 2022). Despite the availability of different energy resources such as solar, hydro, and wind, the city has limited infrastructure to allow the exploitation of those resources, a situation that explains the lack of electricity access in the city.

### 3.4.2. Site description

The city of Kongolo is in the northern part of the province of Tanganyika. The city extends all along the Lualaba River and it is limited to the north by the territory of Kabambare in the province of Maniema, to the south by the city of Kabalo, to the east by the city of Nyunzu, to the west by the city of Lubao in the province of Lomami and the North-West by the territory of Kasongo in the province of Maniema. Kongolo is known for its location vis a vis the Lualaba River, the city is next to the Gates of Hell waterfalls which can shelter a hydroelectric dam for the region. While the majority of the population of Kongolo lives mainly from agricultural trade produced through subsistence farming of maize, peanuts, and rice, the population living along the river practices fishing (CAID, 2020).

### 3.4.3. Load profile estimation of the location

The load requirement is a valuable input for an optimal design of a microgrid. It helps determine the electricity requirement of a household or community which then helps establish the minimum energy service to be catered for. In this study, the load profile was estimated using the Rural Africa Load Profile Explorer tool in conjunction with literature and provincial data availed by ANSER in its local plans for the electrification of the DRC territory released in 2022 (ANSER, 2022). The World Bank, under the SE4ALL initiative, developed the Multi-Tier Framework (MTF) to measure energy access (Power Africa, 2019). Given that household load demand within a community may vary, the framework was used to estimate different household levels which then helped categorize them into three different categories namely high-income households, medium-income households, and low-income households.

### 3.4.4. Household category

An essential part of this study was to understand the different household categories to be served by the system. Since data on the town's household incomes were not available, provincial data were used to determine the different household categories. A conducted study on household income in the DRC showed that household income in the country ranges between $50 (lowest average) and $1600 (highest average). In settlement such as Kongolo, the results of the study implied that approximately 75% of the households earn between $50 and $100, approximately 25% earns between $200 and $400, and less than 5% earns more than $400 (Energy Systems Research Group, 2020).

In this study, households were grouped into 3 categories based on their incomes. Those categories were:

- **Low-income household**: Categorizes households with an income that ranges between $50 and $100.
- **Medium-income household**: Categorizes households with an income that ranges between $200 and $400.
- **High-income household:** Categorizes households with an income of more than $400.

### 3.4.5. Household load profile estimation

The system designed in this study was sized to electrify 200 households and the assumptions made to categorize the households are given in table 8.

Table 8: Repartition of households to be supplied

| | |
|---|---|
| Total number of households | 200 |
| Average persons per household | 6 |
| High-income households | 40 |
| Medium-income households | 60 |
| Low-income households | 100 |

The assumption was made that all households had similar electrical appliances; however, the difference was made in the ownership of those appliances as shown in table 9.

Table 9: Household appliance ownership (%)

| Appliances | High-income household ownership (%) | Medium-income household ownership (%) | Low-income household ownership (%) |
|---|---|---|---|
| Lights | 100 | 100 | 100 |
| Cell phone charger | 96 | 90 | 85 |
| Radio | 71 | 82 | 55 |
| Television | 86 | 83 | 62 |
| Refrigerator | 34 | 8 | 7 |

Ownership of the appliance was taken on the country level as presented by Power Africa Off-grid Project (PAOP) program for households with access to electricity (Power Africa, 2019). It is worth noting that lighting was considered to be available for all households.

After determining households' electrical appliances as well as the ownership per household category, the total hourly usage per household was also determined and shown in table 10.

Table 10: Summary of household load profile (kWh)

| Household category | Total kWh/day/household | Total kWh/year/household: |
|---|---|---|
| High-income | 1.60 | 583.63 |
| Medium income | 0.56 | 206.00 |
| Low-income | 0.41 | 150.00 |

### 3.4.6. Community profile estimation

The community load profile estimation is the solitary input used to determine the total load to be supplied by the system, in other words, it is used to determine the overall size of the system to be developed. The total load profile of all households to be supplied by the system is summarized in table 11 and the community daily load profile is shown in figure 17.

Table 11: Community load profile

| | |
|---|---|
| Total kWh/day | 138.92 |
| Total kWh/year | 50704.85 |
| Max kW/day | 13.88 |
| Min kW/day | 3.81 |

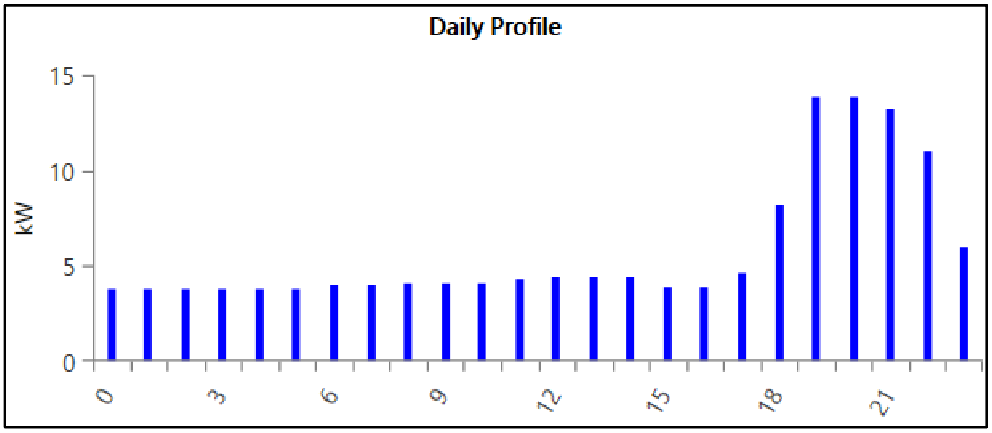

Figure 17: Daily load profile of the community

## 3.5. Software tools used in the study

The two main tools used in this study were the Microgrid Load Profile Explorer and HOMER Pro. There was also an additional software, PVsyst, which was used to preliminary size the solar and storage scope of the system. The next sections will be used to briefly describe each software tool and its performance.

### 3.5.1. HOMER Pro Software

Homer Pro is a global standard optimization tool used for microgrid design in different sectors such as villages, grid-connected villages, and military bases. The software was originally developed by the United State National Renewable Energy Laboratory (NREL) and then was enhanced and distributed by HOMER Energy. It can perform system design optimization as well as sensitivity analysis which would help determine:

- The cost-effective technology
- Suitable component size
- Adequacy of renewable energy supply and storage system

While performing the system design optimization, the software performs multiple simulations to determine the optimal system configuration to meet the technical requirements at the lowest life-cycle cost. During the system design optimization, the suitable system size, and component quantities are determined.

While performing the sensitivity analysis, the software provides assessment results on the effect of uncertainty or changes in the variables that are beyond the control of the designer such as the change in the average of solar radiation, load variation, and change in fuel prices.

### 3.5.2. Microgrid Load Profile Explorer

The microgrid load profile explorer is a tool developed by the NREL to help with the design of electrification systems for Sub Sahara African (SSA) countries. The tool comes in an excel format providing hourly electrical load profiles as well as the minimum and maximum load requirements for different categories of households in SSA (e.g. High-income households, Medium-income households, and Low-income households). It also helps determine the hourly load profile of different community services commonly found in the SSA such as grain milling, small shops, schools, and clinics (*Microgrid Load and LCOE Modelling Results | NREL Data Catalog*, 2018).

### 3.5.3. PVSyst

PVsyst is a tool used to study, size, and analyze the data of a complete PV system. The tool can assess the electricity of a solar system in a specific location by modeling the system while considering all losses in the system. It can deal with different PV systems configurations such as grid-connected, standalone, pumping, and DC-grid while including features such as meteorological input, shading calculations, and carbon balance estimation. PVsyst can also be used to model battery storage systems for different applications such as self-consumption optimization and peak shaving.

## 3.6. Energy resource assessment of Kongolo

### 3.6.1. Solar resource assessment

Section 2 shows DRC's PV potential which presents the country with a considerable potential for Solar PV solutions. As seen in figure 18, the province of Tanganyika is in the Southern-East part of the DRC, which based on solar penetration shown in figure 2, has one of the highest solar PV potentials in the country.


Figure 18: DRC provinces' distribution

During the preliminary energy resource assessment, data from the National Aeronautics and Space Administration (NASA) as obtained from Homer Pro was used in the design of the system. The data estimates the average daily solar radiation in Kongolo, where the system is going to operate, to be around 5.22 kWh/m[2]. Figure 19 shows the daily solar radiation of the location for 12 months.

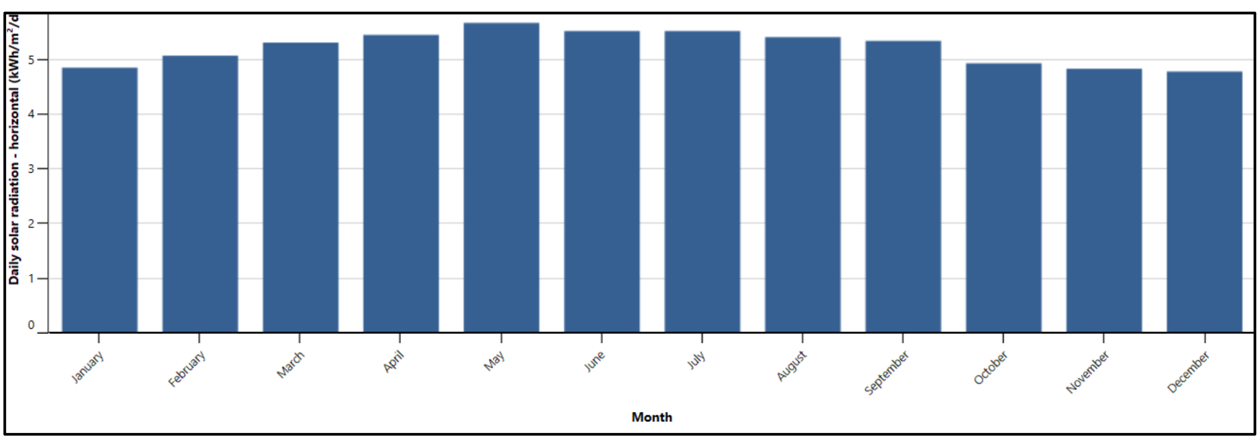


Figure 19: Daily solar radiation of the location in kWh/m[2]

### 3.6.2. Biogas energy resource assessment

DRC possesses considerable potential for biogas for electric power production using raw materials such as animal waste. The country has diversified livestock which predominately consists of goats, pigs, sheep, and cattle (ANAPI, 2022). Based on the provincial data provided by the Ministry of Planning ANAPI, the Tanganyika province possessed approximately 158,751 cattle as of 2015 (ANAPI, 2022). With a hundred of thousand cattle found in the region, cow dung can be widely used as a source of biogas. It is worth noting that the daily manure of a cow depends on multiple factors but largely on feed type, body weight, and nutrition level. A conducted study showed that, in developing countries such as DRC, the body weight of a cow generally varies between 150 kg and 200 kg yielding a daily manure that varies between 10 kg and 15 kg. Table 12 shows different parameters derived from the cow mainly based on the body weight.

Table 12: Different parameters from the cow manure

| **Cow parameters** | **Values** |
|---|---|
| Body weight (kg) | 150 – 200 |
| Daily manure yield (kg) | 10 – 15 |
| Gas yield (m3/kg Total solid, at 25 $^{o}$C) | 25 – 30 |
| Methane (%) | 150 kg: 55 – 65 |
| | 200 kg: 50 – 70 |

The potential biomass production for the region is presented in table 13. The assumption made in this study is that the cattle count is split evenly between the body weight. Conducted studies have shown that 1 kg of cattle dung can produce between 0.037 m$^3$ to 0.04 m$^3$ of biogas (Das *et al.*, 2017). For every 1 m$^3$, there is approximately 60% of methane with a low heating value or calorific value that varies between 21 to 24 MJ/m$^3$, an equivalent of 0.5 liters of diesel fuel or 6 kWh of energy (Das *et al.*, 2017). Methane can also be stored and then acts as an energy storage medium producing fuel to power a biogas generator when required. In this study, the assumption was that 1 kg of cattle dung produces 0.04 m$^3$ of biogas.

Table 13: Potential biogas production for the region

| **Weight (kg)** | **Cattle count** | **Daily manure yield (kg)** | **Daily recovered manure yield (Kg)** | **Gas yield (m$^3$/Kg)** | **Daily biogas production m$^3$** |
|---|---|---|---|---|---|
| 150 | 79,376.00 | 793,760.00 | 595,320.00 | 0.04 | 23,812.80 |
| 200 | 79,376.00 | 1,190,640.00 | 892,980.00 | 0.04 | 35,719.20 |

Given the scarcity of regional data, this study used the available provincial data from which the average daily biomass resource was determined to be 29 tons. Figure 20 shows the monthly livestock resource for 12 months.


Figure 20: Monthly livestock resource from HOMER Pro.

# Chapter 4: System Simulation

## 4.1. Overview

This chapter presents simulation results from HOMER Pro. The system under consideration in this study was configured to supply 200 households with a peak load of 47.45 kW and a daily energy consumption of 139 kWh. Although the study was mainly based on Kongolo, five more sites were also simulated to verify the suitability of the microgrid configuration in different locations of the country. The results presented were for the five different configurations with each having the optimization cost and break-even grid extension distance. the town of Kongolo was used as the main center for the simulation. The optimized results presented were also for the towns of Butembo, Gbadolite, Bolomba, Mweka, and Kolwezi. Kongolo was the only town that was simulated with all different configurations but the other towns were only simulated with the solar PV, battery, and biogas generator configuration. This chapter also presents the sensitivity analysis which was only conducted for the configuration with solar PV, battery, and biogas generator.

## 4.2. Optimization cases

After modeling and simulating a system, the optimization results determine the most optimal system configuration which in this study was defined as the system with the lowest Net Present Cost (NPC) and the lowest Cost of Energy (COE). The optimization results from HOMER are divided into two categories, the overall and the categorized form, respectively. The overall results show all possible configurations of the system in ascending order with respect to the lowest NPC and the categorized results only show the most optimal system configuration. The next paragraphs will present the optimal results of each microgrid configuration in the categorized form.

#### 4.2.1.1. Optimization cases for Kongolo

### (i) Configuration with solar PV

The simulation results showed that there was no possible system configuration to meet the electricity requirement of the community using the solar PV source only. For a system not allowing a capacity shortage, the generation was not enough to meet to load requirement without an energy storage system.

### (ii) Configuration with biogas generator

To meet the load requirement of the microgrid with a biogas generator, the system was configured with a 25 kW generator, and the cost associated with it is summarized in Table 14. The NPC of the system was $283,609 with a COE of $0,384. The required initial cost of the microgrid was $57,500.

Table 14: Description of the microgrid configuration using biogas generator only

| Component | Description |
|---|---|
| Biogas generator (kW) | 25 |
| NPC ($) | 283,609 |
| COE ($/kWh) | 0.384 |
| Operating cost ($/year) | 15,521 |
| Capital Expenditures (CAPEX) ($) | 57,500 |

## (iii) Configuration with solar PV and biogas generator

The optimal microgrid configuration to meet the load requirement using solar PV and a biogas generator at the lowest NPC and COE only required a 25 kW biogas generator. As shown in Figures 21 and 22, the inclusion of solar PV was negligible as it did not have a significant impact on the configuration either in cost or average monthly production. Given that the selected generator was able to fully cater for the load demand, the PV generation was constantly throttled. Table 15 presents the description of the system configuration as well as the cost associated with it. As it can be observed, tables 14 and 15 are similar and that is because in the configuration with solar PV and generator, the generator covers the total load demand, therefore, leaving the system only operating with one source.

| Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|
| Solar PV (kW) | Biogen (kW) | Inverter (kW) | | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| | 25.0 | | | $283,609 | $0.384 | $15,521 | $57,500 |
| 0.363 | 25.0 | 0.0938 | | $284,396 | $0.385 | $15,524 | $58,249 |

Figure 21: Optimal system configuration with solar PV and biogas generator

Table 15: Description of the microgrid configuration using solar PV and a biogas generator.

| Component | Description |
|---|---|
| Biogas generator (kW) | 25 |
| NPC ($) | 283,609 |
| COE ($/kWh) | 0.384 |
| Operating cost ($/year) | 15,521 |
| Capital Expenditures (CAPEX) ($) | 57,500 |

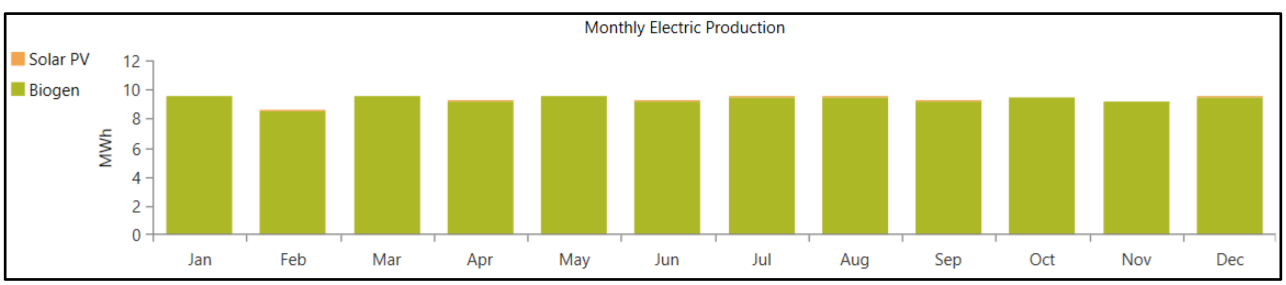

Figure 22: Monthly electricity production from the solar PV and biogas generator

### (iv) Configuration with solar PV and battery energy storage

The optimal microgrid configuration to meet the electricity requirement of the community using solar PV and battery energy storage at the lowest NPC and COE was configured with 81.7 kW of solar PV and 300 kWh of Lithium-ion battery storage as shown in Figure 23. Table 16 shows the full details of the system configuration and costing.

| Architecture | | | Cost | | | |
|---|---|---|---|---|---|---|
| Solar PV (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 81.7 | 3 | 26.3 | $363,593 | $0.492 | $4,039 | $304,757 |

Figure 23: Optimal system configuration with solar PV and battery energy storage

The proposed optimal system configuration had an NPC of $363,593 and the Cost of Energy of $0.492. The required initial cost of the microgrid was $304,757.

Table 16: Description of the microgrid configuration using solar PV and battery storage

| Component | Description |
|---|---|
| Solar PV (kW) | 81.7 |
| Battery energy storage (kWh) | 300 |
| Inverter continuous output (kW) | 26.3 |
| NPC ($) | 363,593 |
| COE ($/kWh) | 0.492 |
| Capital Expenditures (CAPEX) ($) | 304,757 |

### (v) Configuration with solar PV, battery, and biogas generator

To meet the energy requirement of the community using solar PV, battery energy storage, and a biogas generator at the lowest NPC and COE, the optimal microgrid configuration consisted of 41.7 kW of solar PV, 13 kW biogas generator, and 100 kWh of Lithium-ion battery storage as shown in figure 24. Table 17 presents the description of the system configuration, as well as the cost associated with it, and Figure 25, shows the monthly average production of all renewable sources of the system.

| Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|
| Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 41.7 | 13.0 | 1 | 9.57 | $206,664 | $0.318 | $3,079 | $167,203 |

Figure 24: Optimal system configuration with solar PV, battery, and biogas generator

The proposed optimal system configuration had an NPC of $206,664 and a Cost of Energy of $0.318. The required initial cost of the microgrid was $167,203.

Table 17: Description of the microgrid configuration using solar PV, Biogas, and Battery

| Component | Description |
|---|---|
| PV (kW) | 41.7 |
| Biogas generator (kW) | 13 |
| Inverter continuous output (kW) | 9.57 |
| Battery energy storage (kWh) | 100 |
| NPC ($) | 206,664 |
| COE ($/kWh) | 0.318 |
| Capital Expenditures (CAPEX) ($) | 167,203 |

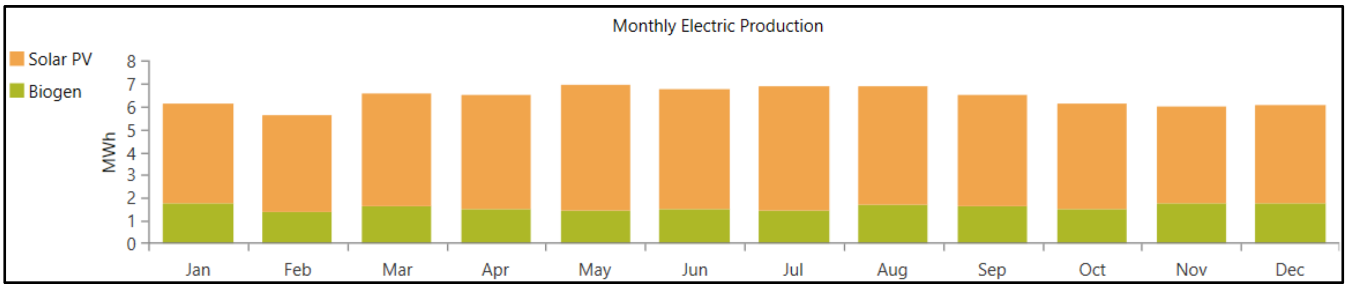


Figure 25: Monthly electricity production from each renewable source

## 4.3. Grid break-even distance for Kongolo

The break-even grid extension distance shows the distance from the grid that makes the extension of the grid a viable solution. It equates the NPC of grid extension with the NPC of a stand-alone microgrid. To complete the grid break-even simulation, the grid's cost of electricity per kWh was taken at $0.07 as per the PAOP report on grid electrification in DRC (Power Africa, 2019). The capital cost was taken as $8000 per km and the operation cost was taken as $200 per km per year. The next paragraphs will present the grid break-even distance of the different configurations as presented in HOMER and how they compare to each other.

### (i) Configuration with solar PV

The grid break-even distance for this configuration could not be determined as the configuration did not present an adequate system size to meet the electricity requirement of the community.

### (ii) Configuration with biogas generator

The break-even grid extension distance for this configuration was 21.25 km as shown in Figure 26, which implies that if the community that is going to be supplied by the microgrid is more than 21.25 km away from the nearest grid, the isolated system with a 25 kW generator only would be a more cost-effective option to supply it.

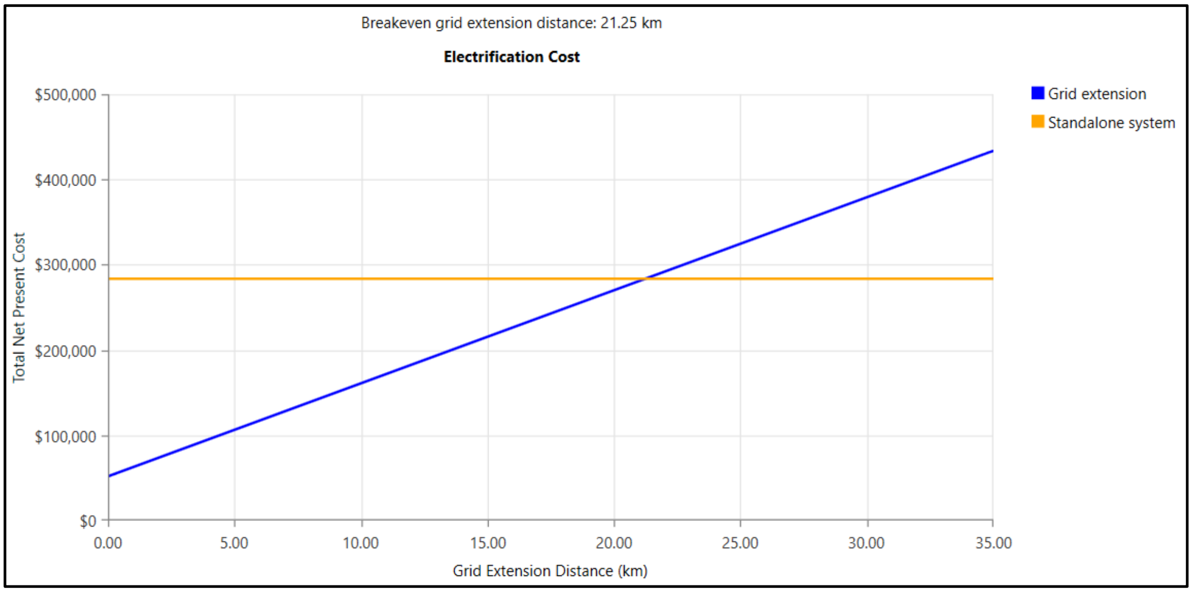


Figure 26: Grid break-even distance graph for the configuration with biogas generator only

### (iii) Configuration with PV and biogas generator

As shown in figure 27, the break-even grid extension distance for this configuration was also 21.25 km as the configuration mainly makes use of the biogas generator and the solar PV contribution is negligible.

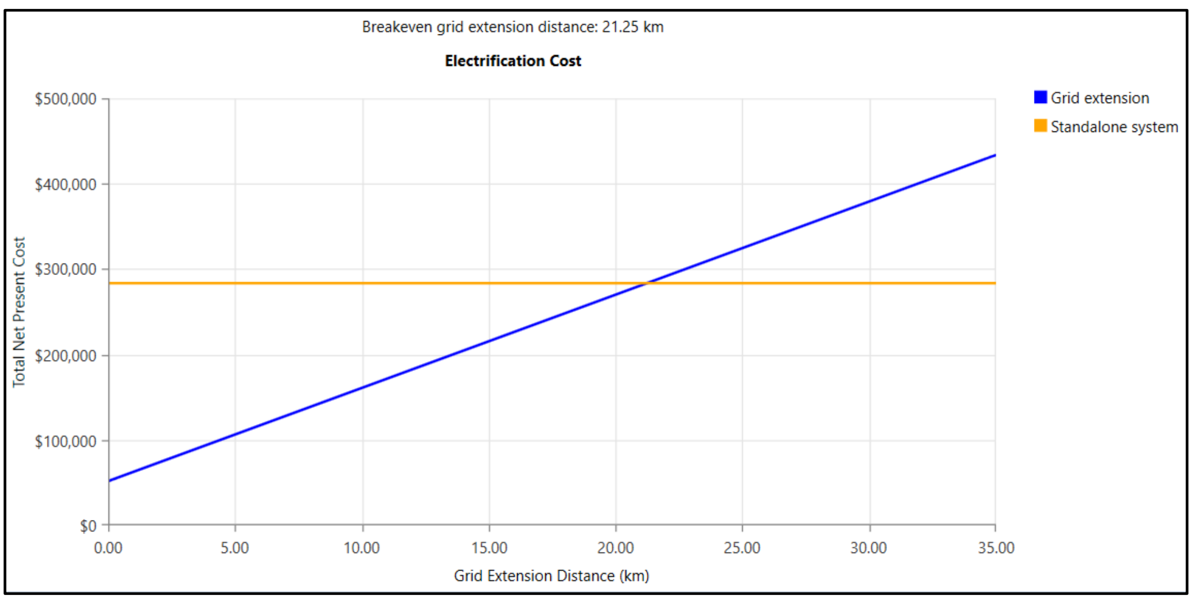


Figure 27: Grid break-even distance graph for the configuration with solar PV and biogas generator

### (iv) Configuration with solar PV and battery energy storage

The break-even grid extension distance for this configuration was 28.58 km as shown in figure 28, which implies that the microgrid configuration with 81.7 kW of solar PV and 300 kWh of battery energy storage was more viable if the load to be supplied was 28.58 km away from the nearest grid.

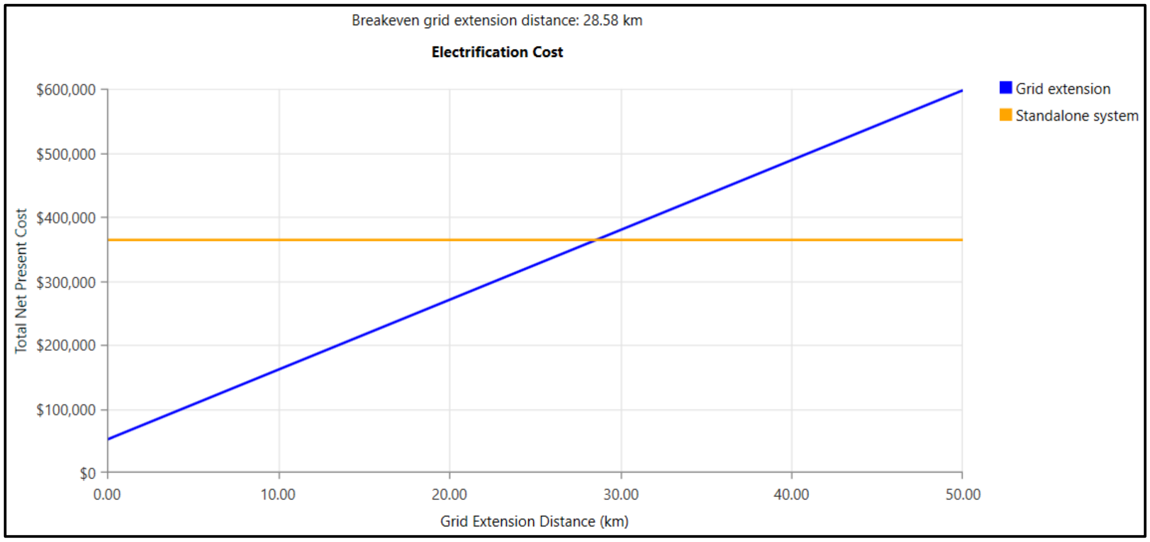


Figure 28: Grid break-even distance graph for the configuration with solar PV and battery energy storage

### (v) Configuration with solar PV, battery, and biogas generator

The break-even grid extension distance for this configuration was 15.26 km as show in figure 29, which implies that if the community is 15.26 km away from the nearest grid, the isolated system with 41.7 kW of solar PV, 13 kW biogas generator, and 100 kWh of battery energy storage would be the most cost-effective option to supply it.

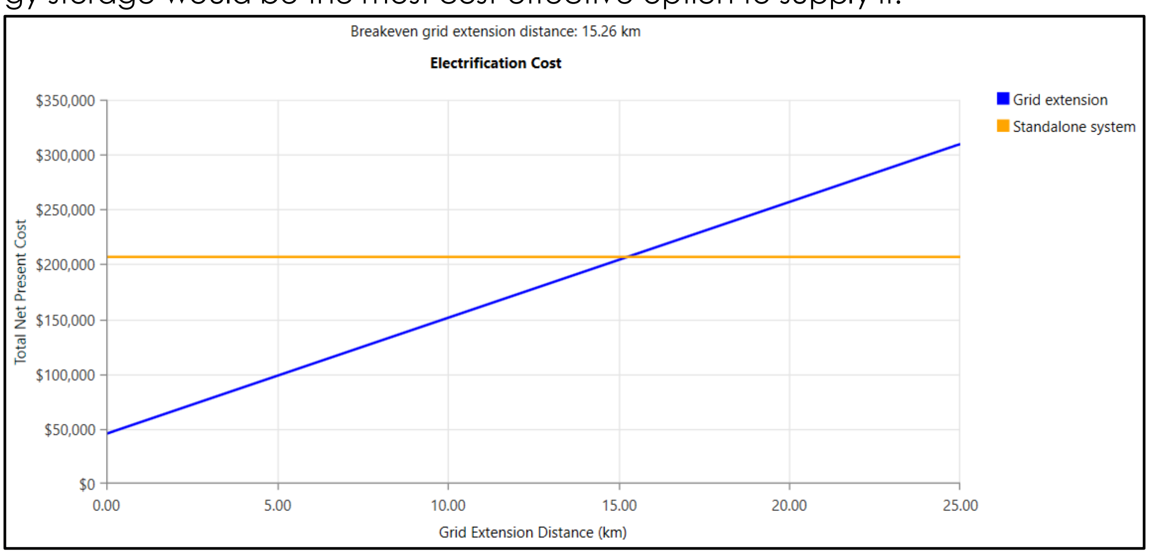


Figure 29: Grid break-even distance graph for the configuration with solar PV, battery energy storage and biogas generator

## 4.4. Optimization case for Butembo

To meet the energy requirement of the Butembo community using solar PV, battery energy storage, and a biogas generator at the lowest NPC and COE, the optimal microgrid configuration consisted of 28.8 kW of solar PV, 13 kW biogas generator, and 200 kWh of Lithium-ion battery storage as shown in figure 30.

| Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|
| Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 28.8 | 13.0 | 2 | 11.3 | $220,010 | $0.338 | $3,764 | $171,770 |

Figure 30: Optimal system configuration for Butembo using solar PV, battery, and biogas generator

Table 18 presents a detailed description of the system configuration, as well as its costs.

Table 18:Description of the microgrid configuration for Butembo and its costs

| Component | Description |
|---|---|
| PV (kW) | 28.8 |
| Biogas generator (kW) | 13 |
| Inverter continuous output (kW) | 11.3 |
| Battery energy storage (kWh) | 200 |
| NPC ($) | 220,010 |
| COE ($/kWh) | 0.338 |
| Capital Expenditures (CAPEX) ($) | 171,770 |

As shown in Figure 31, the break-even grid distance for the system configuration was 16.25 km implying that this microgrid configuration is more suitable to supply the Butembo community compare to extending the grid which is more than 16.25 km away from the community.

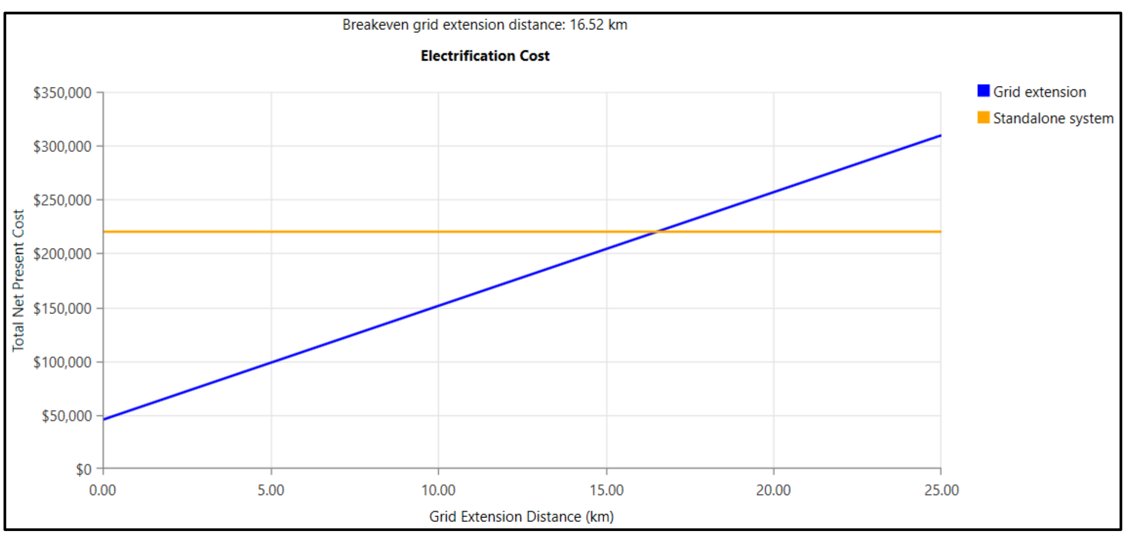


Figure 31: Grid break-even distance graph for microgrid configuration in Butembo

## 4.5. Optimization case for Gbadolite

To meet the energy requirement of the Gbadolite community using solar PV, battery energy storage, and a biogas generator at the lowest NPC and COE, the optimal microgrid configuration consisted of 28 kW of solar PV, 13 kW biogas generator, and 200 kWh of Lithium-ion battery storage as shown in figure 32.

| Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|
| Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 28.0 | 13.0 | 2 | 10.3 | $219,227 | $0.337 | $3,836 | $170,072 |

Figure 32: Optimal system configuration for Gbadolite using solar PV, battery, and biogas generator.

Table 19 presents a detailed description of the system configuration, as well as the cost associated with it.

Table 19: Description of the microgrid configuration for Gbadolite and its costs

| **Component** | **Description** |
|---|---|
| PV (kW) | 28 |
| Biogas generator (kW) | 13 |
| Inverter continuous output (kW) | 10.3 |
| Battery energy storage (kWh) | 200 |
| NPC ($) | 219,227 |
| COE ($/kWh) | 0.337 |
| Capital Expenditures (CAPEX) ($) | 170,072 |

As shown in Figure 33, the break-even grid distance for the system configuration was 16.45 km which makes it a more suitable system to electrify the community than extending the grid beyond that distance away from the community.

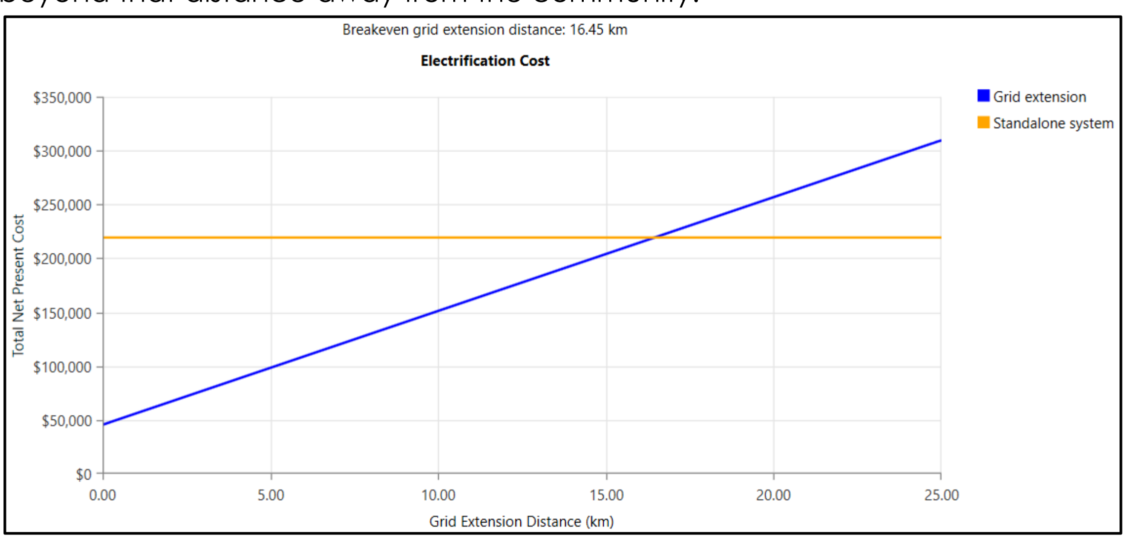


Figure 33: Grid break-even distance graph for microgrid configuration in Gbadolite

## 4.6. Optimization case for Bolomba

For the Bolomba community, the system with the lowest NPC and COE was configured with 30.7 kW of solar PV, 13 kW biogas generator, and 200 kWh of Lithium-ion battery storage as shown in Figure 34. Table 20 presents a detailed description of the microgrid configuration, as well as the cost associated with it.

| Architecture | | | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|---|
| Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | | | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 30.7 | 13.0 | 2 | 10.6 | | | $224,303 | $0.345 | $3,803 | $175,570 |

Figure 34: Optimal system configuration for Bolomba using solar PV, battery, and biogas generator.

Table 20: Description of the microgrid configuration for Bolomba and its costs

| **Component** | **Description** |
|---|---|
| PV (kW) | 30.7 |
| Biogas generator (kW) | 13 |
| Inverter continuous output (kW) | 10.6 |
| Battery energy storage (kWh) | 200 |
| NPC ($) | 224,303 |
| COE ($/kWh) | 0.345 |
| Capital Expenditures (CAPEX) ($) | 175,570 |

Figure 35 shows that the break-even grid distance of the system configuration was 16.93 km which implies that the system is more suitable than extending the grid which is beyond 16.93 km to electrify the Bolomba community.

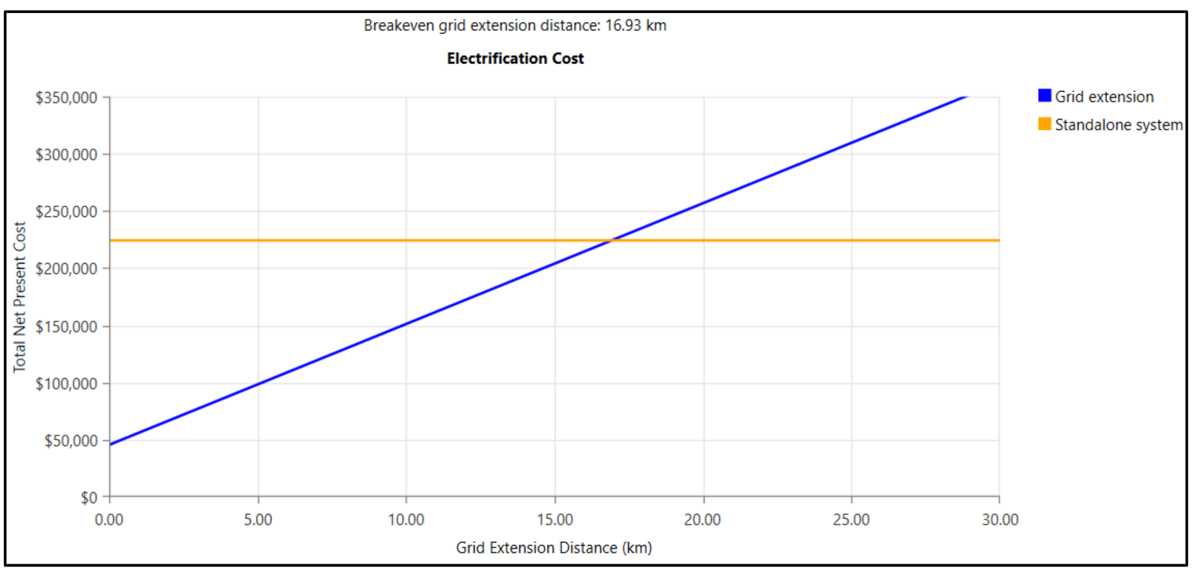


Figure 35: Grid break-even distance graph for microgrid configuration in Bolomba

## 4.7. Optimization case for Mweka

To meet the energy requirement of the Mweka community using solar PV, battery energy storage, and a biogas generator at the lowest NPC and COE, the optimal microgrid configuration consisted of 27.7 kW of solar PV, 13 kW biogas generator, and 200 kWh of Lithium-ion battery storage as shown in figure 36. Table 21 presents a detailed description of the system configuration and its costs.

| Architecture | | | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| | 27.7 | 13.0 | 2 | 9.76 | $220,477 | $0.339 | $3,999 | $169,227 |

Table 21: Description of the microgrid configuration for Mweka and its costs

| Component | Description |
|---|---|
| PV (kW) | 27.7 |
| Biogas generator (kW) | 13 |
| Inverter continuous output (kW) | 9.76 |
| Battery energy storage (kWh) | 200 |
| NPC ($) | 220.477 |
| COE ($/kWh) | 0.339 |
| Capital Expenditures (CAPEX) ($) | 169,227 |

Figure 37 shows that the break-even grid distance for the system configuration was 16.56 km which implying that the system this microgrid configuration is more suitable to supply the Butembo community than extending the grid if it is more than 16.56 km away from the community.

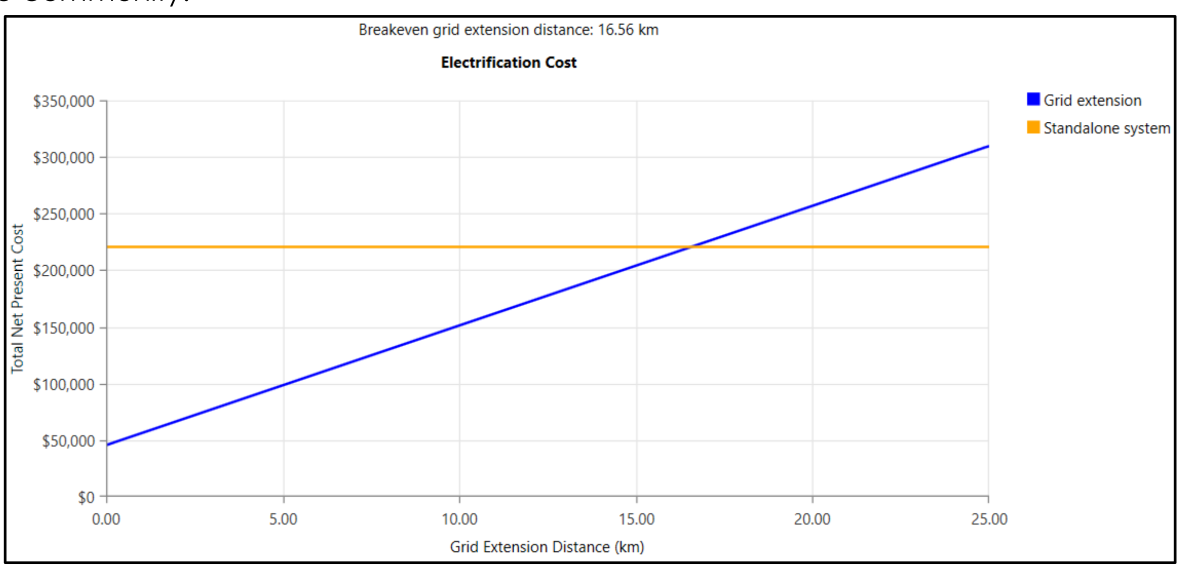


Figure 37: Grid break-even distance graph for microgrid configuration in Mweka

## 4.8. Optimization case for Kolwezi

To meet the energy requirement of the Kolwezi community using solar PV, battery energy storage, and a biogas generator at the lowest NPC and COE, the optimal microgrid configuration consisted of 31 kW of solar PV, 13 kW biogas generator, and 100 kWh of Lithium-ion battery storage as shown in figure 38.

| Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|
| Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 31.0 | 13.0 | 1 | 11.8 | $184,705 | $0.284 | $2,994 | $146,338 |

Figure 38: Optimal system configuration for Kolwezi using solar PV, battery, and biogas generator

Table 22 presents a detailed description of the system configuration, as well as the cost associated with it.

Table 22: Description of the microgrid configuration for Kolwezi and its costs

| **Component** | **Description** |
|---|---|
| PV (kW) | 31 |
| Biogas generator (kW) | 13 |
| Inverter continuous output (kW) | 11.8 |
| Battery energy storage (kWh) | 100 |
| NPC ($) | 184,705 |
| COE ($/kWh) | 0.284 |
| Capital Expenditures (CAPEX) ($) | 146,338 |

As shown in Figure 39, the break-even grid distance for the system configuration was 13.18 km implying that the system this microgrid configuration is more suitable to supply the Butembo community than extending the grid if it is more than 13.18 km away from the community.

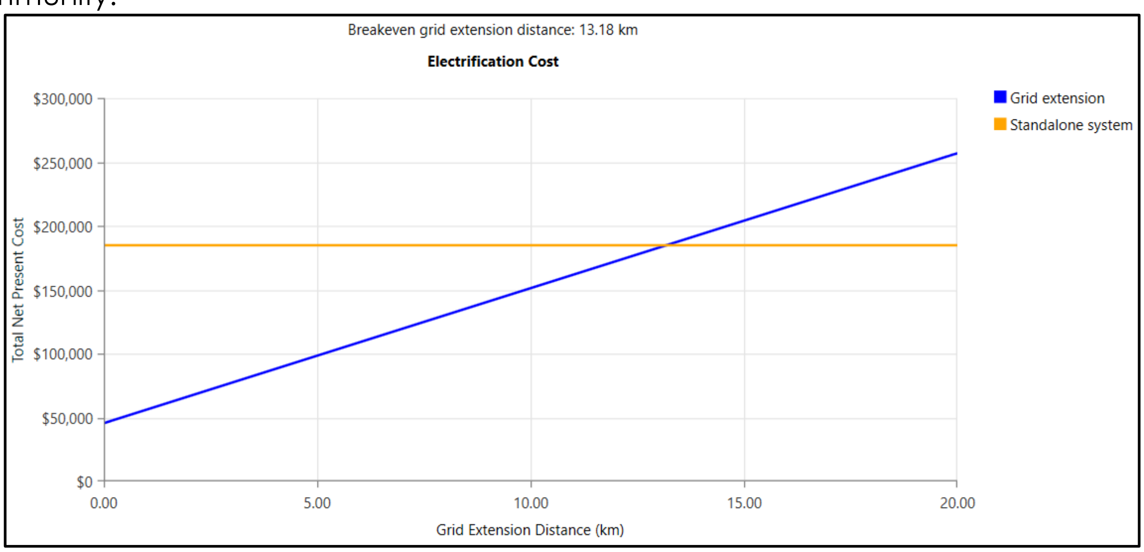


Figure 39: Grid break-even distance graph for microgrid configuration in Kolwezi

## 4.9. Sensitivity cases

The simulation results on HOMER Pro are largely based on its inputs. However, those inputs can be variable due to multiple external factors such as the variation in renewable energy resources, change in load demand, etc. To account for those variations, an analysis taking into consideration the variation of input values is of great importance in the system design. To account for the variation caused by other external factors, HOMER Pro offers a variation assessment with its sensitivity analysis function. A sensitivity analysis is an assessment performed in HOMER Pro based on multiple input variables. In this study, the sensitivity analysis was only conducted on the configuration that consisted of solar PV, battery energy storage, and a biogas generator. The variations taken into consideration for the sensitivity analysis were the change in the community's electricity demand and the availability of biomass resources.

### 4.9.1. Sensitivity analysis based on the variation in electricity demand

The sensitivity analysis on the electricity demand was performed to understand the effect of the increased electricity demand on the system costs, component size, and the grid break-even distance. The increased electricity demand is likely to occur due to additional connections to the system because of the availability of electrical energy in the community. The analysis was done based on 0, 25, 50, 75, and 100 % increases.

Figure 40 shows the impact of the increase in load requirement on the system component and cost. For every percentage change in the load requirement, there is a need for an increase in either the solar PV or the battery energy storage capacity. Table 23 shows the summarized results of all variations in the electricity demand.

| Sensitivity | | | Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NominalDiscountRate (%) | Electric Load Scaled Average (kWh/d) | Biomass Scaled Average (tonne/day) | Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 12.0 | 139 | 29.0 | 41.7 | 13.0 | 1 | 9.57 | $206,664 | $0.318 | $3,079 | $167,203 |
| 12.0 | 174 | 29.0 | 52.7 | 13.0 | 3 | 16.3 | $302,356 | $0.372 | $4,020 | $250,844 |
| 12.0 | 209 | 29.0 | 104 | 13.0 | 3 | 34.4 | $402,357 | $0.412 | $3,405 | $358,722 |
| 12.0 | 243 | 29.0 | 110 | 13.0 | 4 | 26.0 | $453,985 | $0.400 | $4,404 | $397,547 |
| 12.0 | 278 | 29.0 | 151 | 13.0 | 4 | 40.1 | $535,790 | $0.412 | $4,158 | $482,501 |

Figure 40: Sensitivity analysis using the different increases in electricity demand

A 25% increase in load demand would require an increase of the solar PV component by 26% and the battery energy storage by 200% leading to an increase in the cost of energy by 16.9%. If the load requirement was increased by 50%, the size of the solar PV would need to be increased by 149%, and the battery energy storage by 200%. The continuous output of the inverter would also be 14.6% larger than the 30 kW continuous power of the inverter configured in the initial system and all that would result in a 29.5% increase in the cost of energy. If the load requirement was increased by 75%, the solar PV component would need to be increased by 163% and the battery storage by 300%

leading to a 25.7% increase in the cost of energy. A 100% in load requirement would require an increase of the solar PV component by 263% and the battery energy storage by 300%. The continuous output power of the inverter would also be 33.6% larger than the 30 kW of the initially installed inverter and all the changes would lead to a 29.5% increase in the cost of energy.

Table 23: Results obtained from the sensitivity analysis on demand increase

| **Increase in electricity demand (%)** | **0** | **+25** | **+50** | **+75** | **+100** |
|---|---|---|---|---|---|
| PV size (kW) | 41.7 | 52.7 | 104 | 110 | 151 |
| Inverter continuous output (kW) | 9.57 | 16.3 | 34.4 | 26 | 40.1 |
| Battery storage size (kWh) | 100 | 300 | 300 | 400 | 400 |
| NPC ($) | 206,664 | 302,356 | 402,357 | 453,985 | 535,790 |
| COE ($) | 0.318 | 0.372 | 0.412 | 0.4 | 0.412 |

As the microgrid size increased due to the increase in the load requirement, the grid break-even distance also increase. As shown in figures 41 to 44, the grid break-even distance would change to 23.23 km, 31.61 km, 35.45, and 42.11 km for an increase in load requirement of 25, 50, 75, and 100 % respectively.

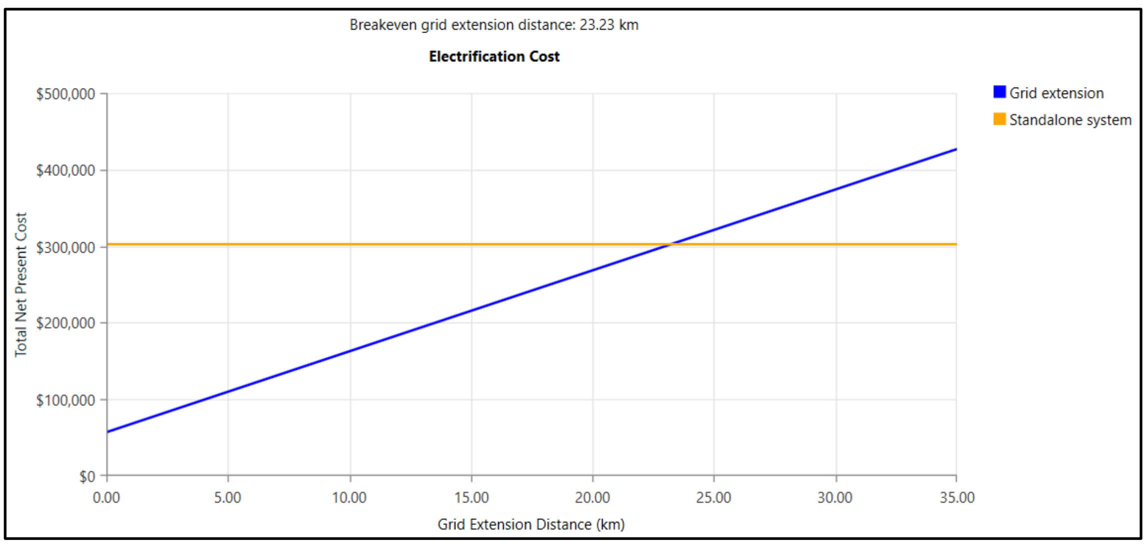

Figure 41: Grid break-even distance of the optimum system after 25% load increase

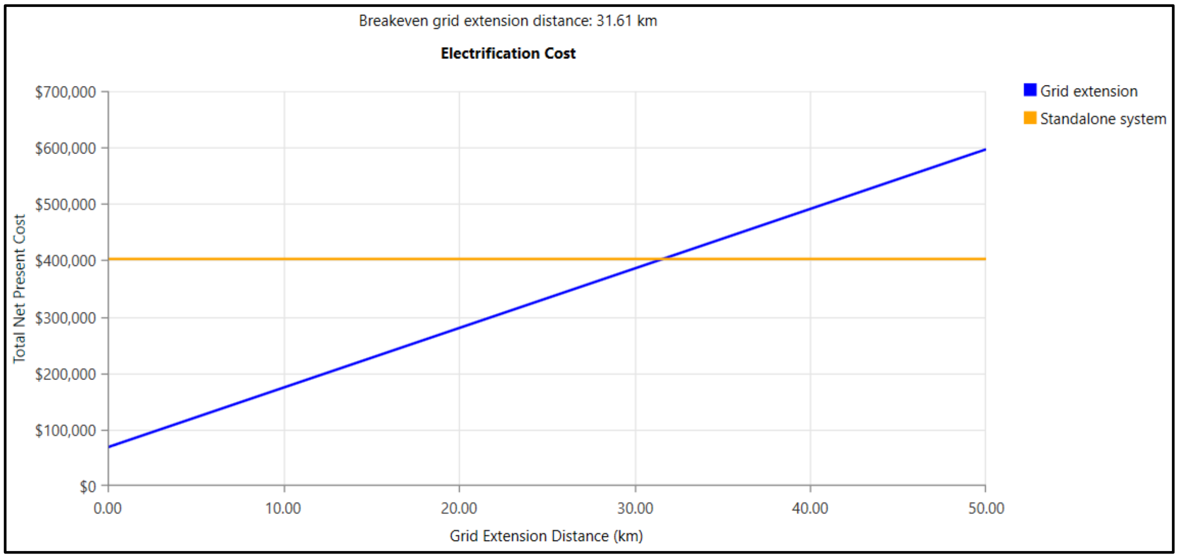


Figure 42:Grid break-even distance of the optimum system after 50% load increase

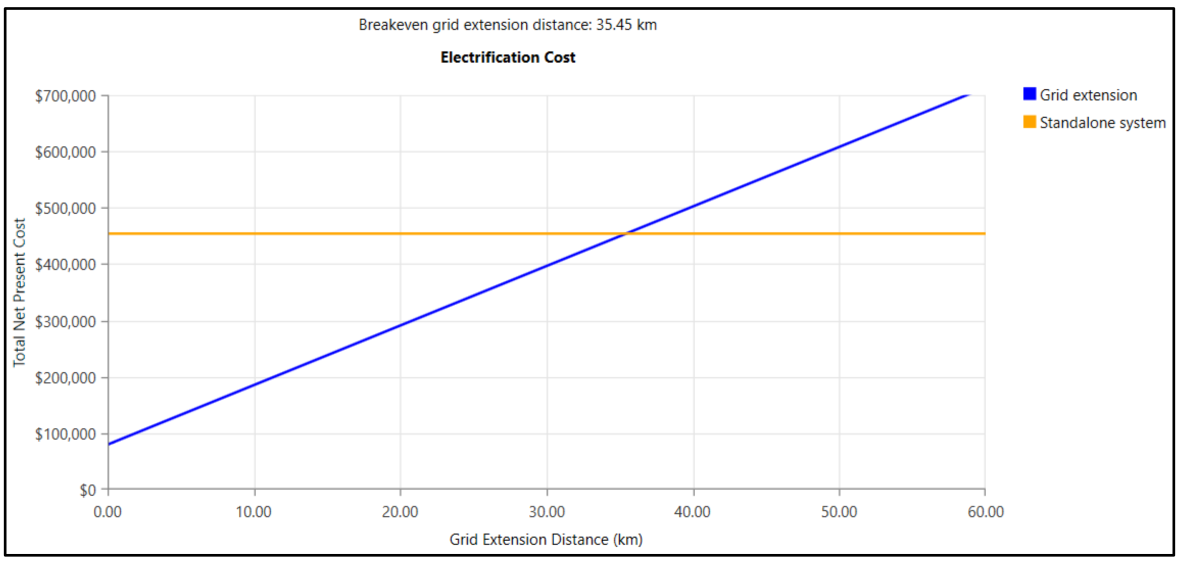


Figure 43: Grid break-even distance of the optimum system after 75% load increase

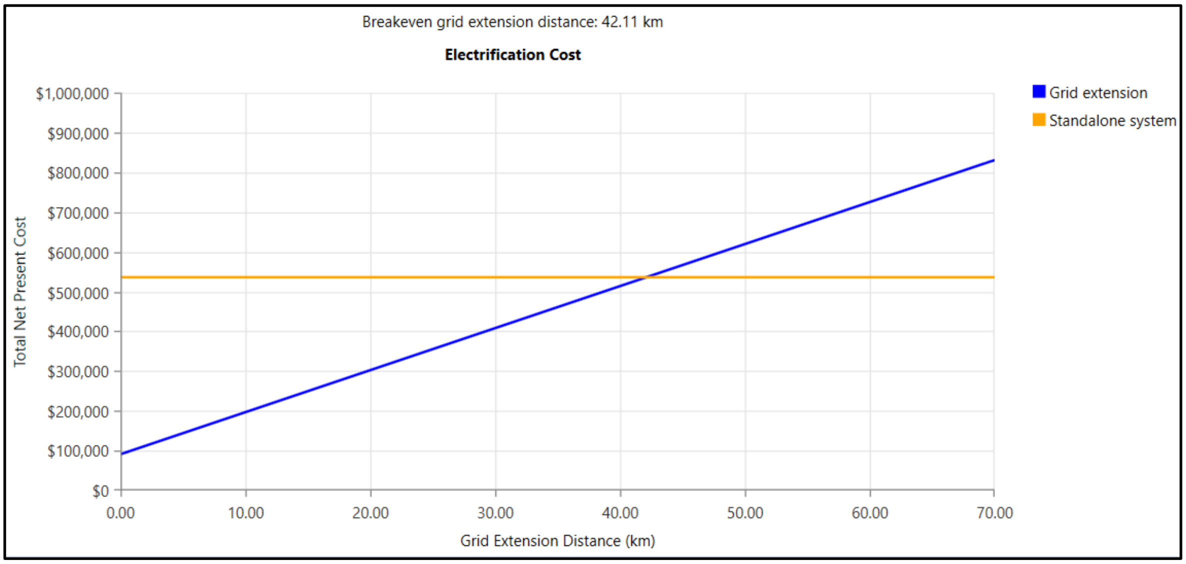

Figure 44: Grid break-even distance of the optimum system after 100% load increase

### 4.9.2. Sensitivity analysis based on the availability of biomass

The sensitivity analysis on the biomass resource was performed to determine how the scarcity of the biomass resource will affect the system size and cost. The analysis considered 29, 19, and 9 tons of average biomass resources per day. As shown in Figure 45, the depletion of biomass resources would not affect the sizes of the microgrid's components or its cost. Table 24 shows the summarized result of the sensitivity analysis on biomass resources.

| Sensitivity | | | Architecture | | | | Cost | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NominalDiscountRate (%) | Electric Load Scaled Average (kWh/d) | Biomass Scaled Average (tonne/day) | Solar PV (kW) | Biogen (kW) | Battery bank (#) | Inverter (kW) | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) |
| 12.0 | 139 | 19.0 | 41.7 | 13.0 | 1 | 9.57 | $206,664 | $0.318 | $3,079 | $167,203 |
| 12.0 | 139 | 29.0 | 41.7 | 13.0 | 1 | 9.57 | $206,664 | $0.318 | $3,079 | $167,203 |
| 12.0 | 139 | 9.00 | 41.7 | 13.0 | 1 | 9.57 | $206,664 | $0.318 | $3,079 | $167,203 |

Figure 45: Sensitivity analysis with different biomass resource availability

Table 24: Sensitivity analysis results on biomass resources availability

| Availability of biomass (Average in tons/day) | 29 | 19 | 9 |
|---|---|---|---|
| PV size (kW) | 41.7 | 41.7 | 41.7 |
| Biogas generator size (kW) | 13 | 13 | 13 |
| Inverter continuous output (kW) | 9.57 | 9.57 | 9.57 |
| Battery storage size (kWh) | 100 | 100 | 100 |
| NPC ($) | 206,664 | 206,664 | 206,664 |
| COE ($) | 0.318 | 0.318 | 0.318 |

# Chap 5: Results discussion

## 5.1. Overview

This chapter discusses simulation results from HOMER Pro. The chapter comparatively discusses all results and then validates the most viable microgrid configuration for the electrification of the community under study. The chapter also validates the implementation of the most suitable microgrid configuration in multiple locations of the DRC.

## 5.2. Optimized cases for Kongolo

This research project aimed to develop a microgrid consisting of solar PV and energy storage to electrify the town of Kongolo in the province of Tanganyika in DRC. The town is located just over 20 km away from the nearest existing grid and the cost of extending the grid to the town was considered as less viable compared to developing a local microgrid with a renewable energy source. ANSER, which is a national institution tasked with the improvement of electricity access in rural and remote areas in the DRC has also focused its plan to electrify the province of Tanganyika mainly with solar systems (ANSER, 2023). After identifying standalone microgrids as the most viable solution to electrify the town, the next step was to identify the most suitable microgrid configuration using solar PV, energy storage, and other available resources in the region. The configuration was to provide sustainable electricity access at a lower cost than extending the nearest existing grid.

To determine the most suitable microgrid configuration for Kongolo, five different configurations were considered:

- Microgrid with solar PV.
- Microgrid with biogas generator.
- Microgrid with solar PV and biogas generator.
- Microgrid with solar PV and battery energy storage.
- Microgrid with solar PV, battery energy storage, and biogas generator.

From the five different configurations, the one with solar PV only could not meet the electricity requirement of the community. The reason why the system was not able to meet the electricity demand was that one of the requirements of the system was a 0% capacity shortage. Given that solar PV would not be able to cater to the load demand during night-time, where the demand is highest, that configuration was not able to provide a sustainable solution and was excluded from the mix.

After the exclusion of the microgrid with solar PV configuration, the comparison remained mainly between the other four configurations. The optimum component sizing of each microgrid configuration is presented in Table 25. C1 represents the microgrid configured with solar PV only, C2 represents the configuration with a biogas generator only, C3 represents the one with solar PV and biogas generator, C4 represents the one with solar PV and battery energy storage and C5 represents the configuration with solar PV, battery energy storage and biogas generator.

Table 25: Component sizes and costs of different microgrid configuration

| Configuration | PV (kW) | Battery (kWh) | Biogen (kW) | Inverter (kW) |
|---|---|---|---|---|
| C1 | - | - | - | - |
| C2 | - | - | 25 | - |
| C3 | - | - | 25 | - |
| C4 | 81.7 | 300 | - | 26.3 |
| C5 | 41.7 | 100 | 13 | 9.57 |

As observed in Table 25, C2 and C3 have similar component sizes although solar PV was only introduced in C3. The reason for that was because the contribution of the solar PV into C3 was minimal and could be neglected leaving the generator to cater for the load demand. Also as indicated in the above paragraph, the microgrid configuration with solar PV only could not meet the load demand for a 0% capacity shortage requirement and given that solar power is at its peak for approximately three to four hours a day when the demand is lowest, its contribution did not have a significant impact.

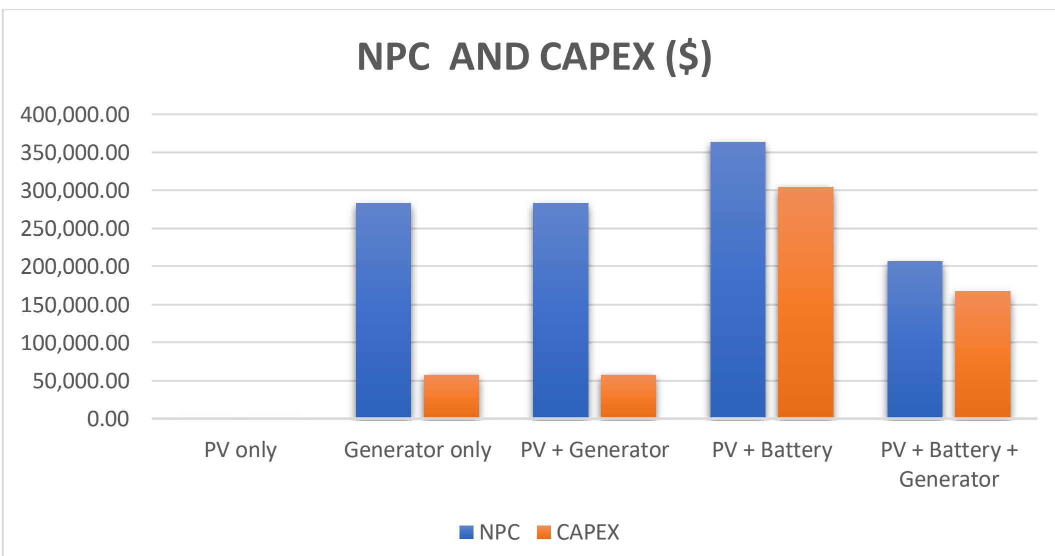


Figure 46: Cost comparison (NPC and CAPEX) of the five different microgrid configuration

As observed in Figure 46, C4 presented the configuration with the highest cost, therefore leaving the final comparison between C3 and C5. The capital expenditure of C5 was 190% higher than that one of C3. The reason for that was that C3 would not require a lot of finance at the start of the project compared to C5 as it only had one major component which was the generator. However, considering the lifetime of the project, C5 presented the most cost-effective configuration as the NPC and COE of C3 were 37.2 % and 20.8 % higher respectively. Figure 47 shows the COE comparison of the five system configurations.

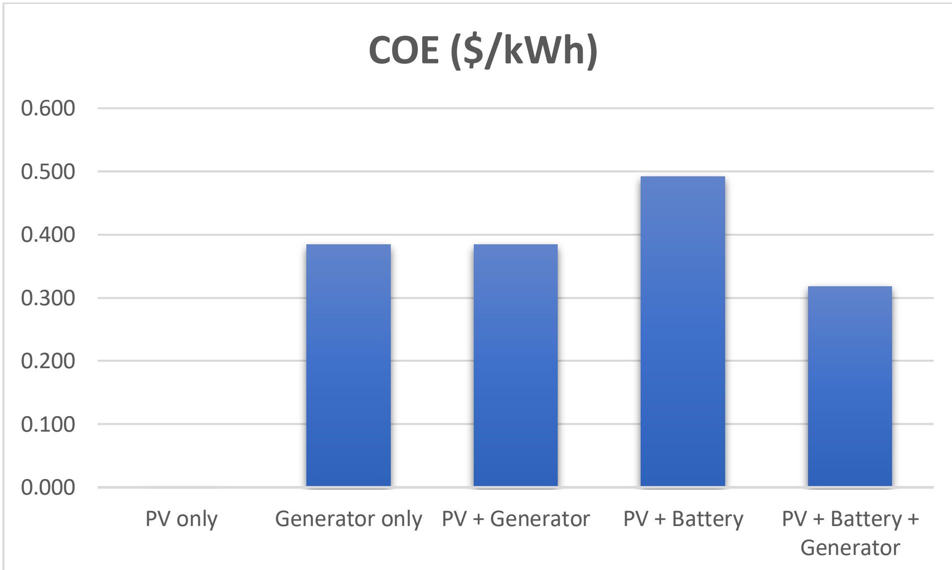


Figure 47: Cost comparison (COE) of the five different microgrid configuration

Figure 48 shows how C5, which is the most cost-effective configuration, compares to the COE of the existing systems in the country. While SNEL customers, which are already in a subsidized tariff, pay an average of 0.21 $/kWh, the COE across all other power sources, including diesel generators goes up to 0.80 $/kWh [6][7]. Although the COE paid by SNEL customers is lower than the one paid by the customers who would use the microgrid presented in this study, SNEL service is intermittent and unavailable for more than 75 percent of the day [9]. When looking at other power sources, which are generally diesel generators, it shows that unattended SNEL customers spend more than 150% more by using generators than they will be using the microgrid presented in this study. Given that SNEL services are available for less than 25% of the day, it means that SNEL customers spend 0.652 $/kWh to have access to electricity the whole day when using diesel generators for the remaining 75% of the day. That makes the COE of the microgrid presented in this study less than 50% cheaper than the actual COE paid by SNEL customers.

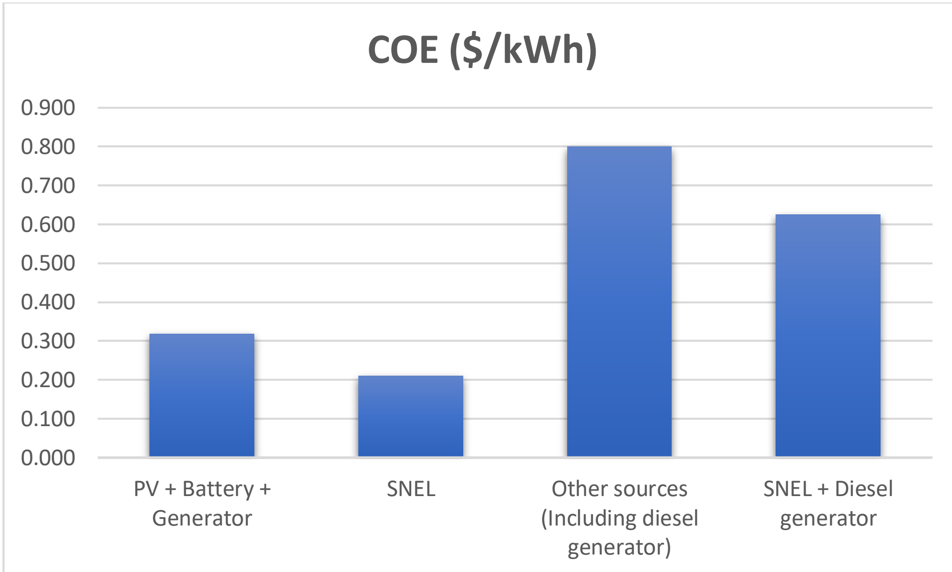


Figure 48: Cost comparison (COE) of solar PV microgrid and actual cost paid by SNEL customers

Apart from the lowest cost yielded by C5, it also presented the configuration with the shortest grid break-even distance as observed in Figure 48. Given that Kongolo is about 20 km away from the nearest existing grid, the break-even distance of 15.26 km did not only make it the most suitable configuration amongst all the others but also made it the most suitable techno-economic configuration compared to extending the grid to electrify the town.

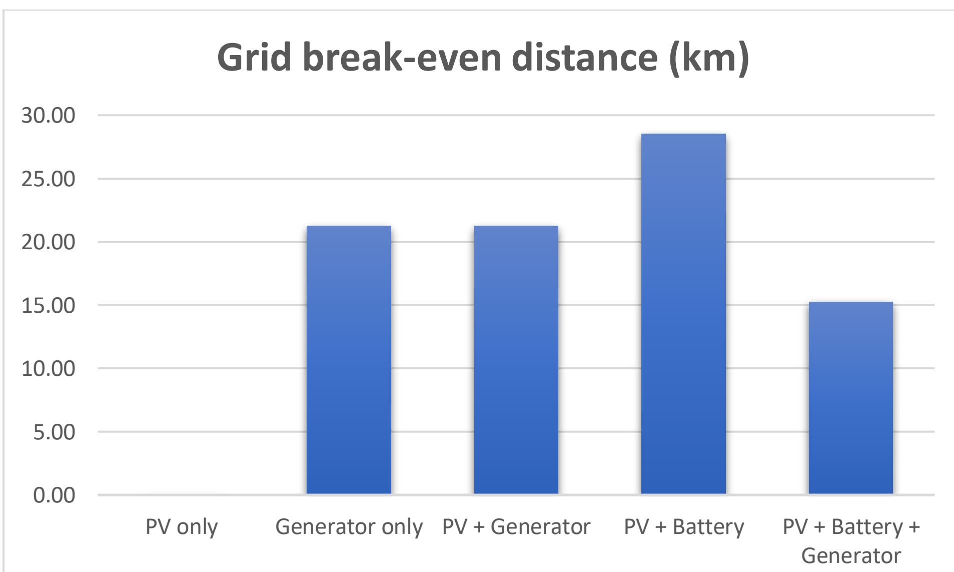


Figure 49: Grid break-even distance of the five microgrid configurations

## 5.3. Optimized case of other locations

The microgrid configuration with solar PV, battery energy storage, and biogas generator appeared to be a suitable configuration across multiple locations in the country. As observed in Figure 49, the highest NPC is $224,303 and that is only 8.5% higher than the cost of the system designed for Kongolo. The lowest NPC is $184,705 which makes the system designed for Kongolo11.8% more expensive.

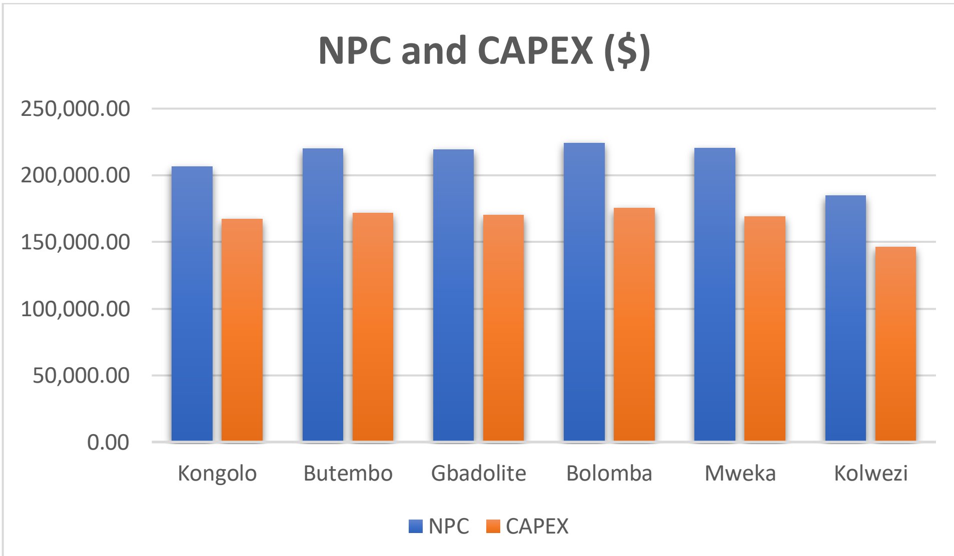


Figure 50: Cost comparison (NPC and CAPEX) for the other locations of the country

The grid break-even distance was also below 20 km in all the locations as shown in Figure 50, indicating that the microgrid configuration is more suitable than the grid extension in multiple locations in the country given that the nearest grid in all locations considered is further than 20 km away.

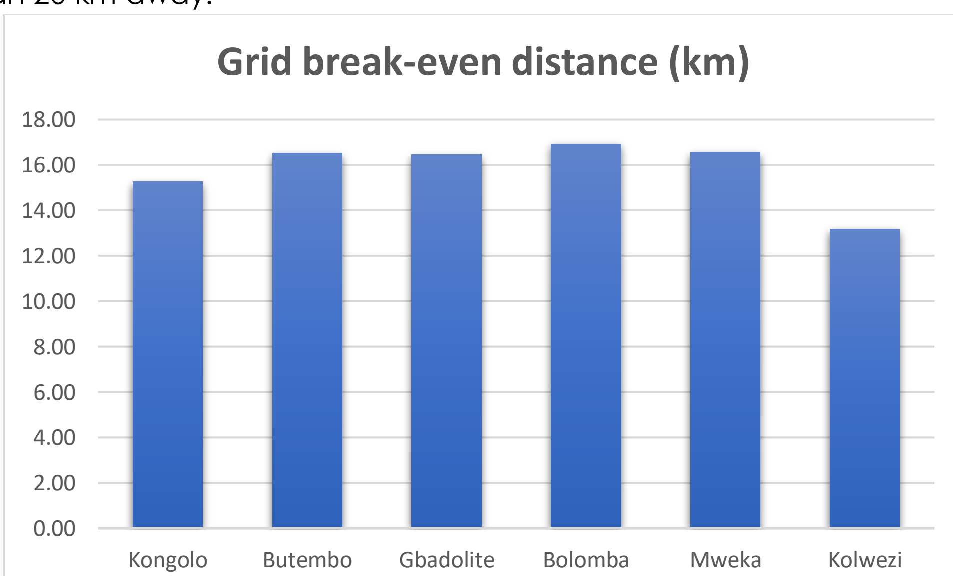


Figure 51: Grid break-even distance for the other locations in the country

## 5.4. Sensitivity analysis

After validating that the microgrid configured with 41.7 kW solar PV, 100 kWh Lithium-ion battery storage, and 13 kW biogas generator could electrify Kongolo, it was also important to determine if the system could accommodate a change in the load requirement. Electricity access in town would potentially lead to an increase in load requirement as the community could use the opportunity to procure more electrical appliances that there were not able to use initially due to the lack of electricity. To determine the effect of the change in load requirement on the system, four scenarios were considered which were a 25, 50, 75 and 100 % increase. The impact of those changes on the sizes of the equipment in the microgrid and the costs can be observed in Table 23. There was at least a 16% change in the sizes of all components in the system and that went up to 300%.

Another factor considered in this study was the grid break-even distance as shown in Figure 52. In case of a 25% load increase, the grid break-even distance increased to 23.23 km. Given that the town is just over 20 km away from the existing grid, this system can still present a suitable techno-economic configuration for the town. However, for any increase above that, the grid extension becomes a more viable option to electrify the town.

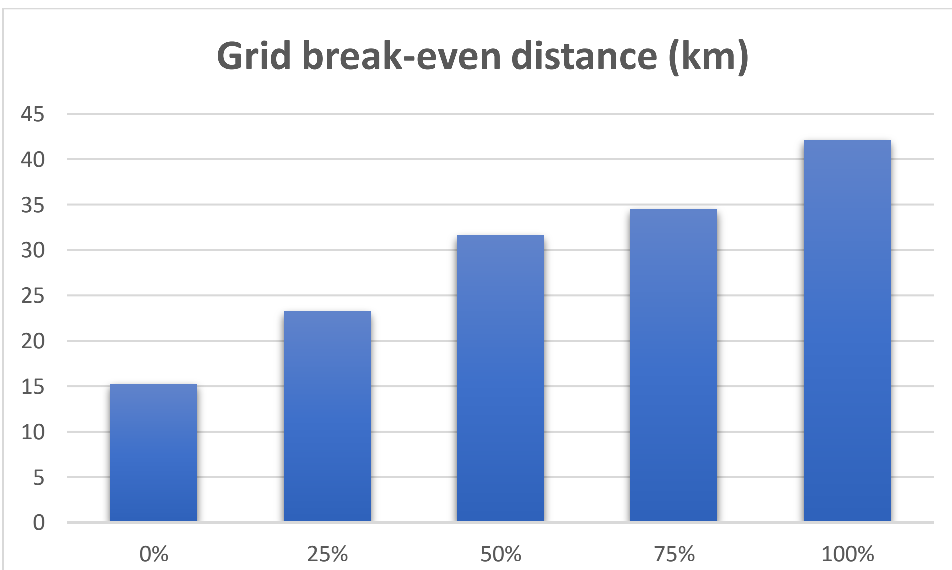


Figure 52: Grid break-even distance for the optimum configuration with the increase in load

Another aspect looked at after validating the change in the microgrid configuration based on the availability of biomass resources. What would be the impact of scarcity in biomass resources on the sizes of the component in the system or its cost? To determine the results of that change, 2 scenarios were considered which were a decrease in the average of resources availability by 10 and 20 tons per day. As observed in Table 24, the changes did not have any impact on the system components and costs.

# Chap 6: Conclusion and Recommendations

This research project aimed at developing a solar PV microgrid with an ESS to provide sustainable electricity access in Kongolo, a town located in the province of Tanganyika in the DRC. Renewable energy-based microgrids such as the one developed in this study are regarded as a possible solution to addressing the ongoing issue of low electricity access rates in remote communities of SSA countries. Some of the advantages they possess over the traditional grid are that they can be developed where they are going to be used and they make use of locally available resources contrary to the traditional grid which are generally standing thousands of kilometers away from remote locations and do not possess adequate infrastructures to services them from that distance.

## 6.1. Answer research questions

This section presents answers to the research question as emerged from the research work completed.

- **Will the developed microgrid provide sustainable and affordable electricity to the users?**

The units used to measure the sustainability of the microgrid under consideration in this study were the electricity production for direct use, the cost of the system, and the electricity production for foreseeable future use. The microgrid designed in the study did not allow for electricity shortage as it was designed to cater to the community load requirement at any given time of the day and throughout the year. DRC has one of the lowest average electricity tariffs of 0.07$/ kWh, which is highly subsidized (Power Africa, 2019). For a sustainable microgrid, the tariff structure should balance the needs of the government, the developers, and the customers. To cater to that balance, the Ministry of Energy in DRC approved a tariff structure of 0.210 $/kWh to the Société Congolaise de Distribution d'Eau et d'Electricité (SOCODEE), which is one of the country's entities that supply electricity to the public. If the microgrid under consideration in this study was to match that tariff structure, a subsidy of 0.108$/kWh would be required. Given that the microgrid developed in this study is renewable energy-based with no possibility of a shortage, the subsidy could be used as a trade-off with the conventional network currently used in the country with intermittent electricity supply. A conducted study by PAOP showed that for a 100-household village in Ghana and Tanzania, a solar PV microgrid with battery energy storage and diesel generator will require a tariff between 0.750 $/kWh and 0.800 $/kWh. To be able to match the existing national tariff in those countries, a subsidy of approximately 0.400 $/kWh and 0.500 $/kWh would be required to cover the developer revenue gap (Reber *et al.*, 2018). The comparison between the cost and subsidy required from the systems in those two countries and the one obtained from the microgrid developed in this study shows the suitability of the microgrid developed in this study.

- **What Energy Storage System or additional renewable source will be suitable for the microgrid configuration under consideration?**

Given that no power shortage was allowed in the microgrid under consideration in this study, it was necessary to include an energy storage system to meet the load requirement in the event of a shortage of solar supply. The battery energy storage system was a suitable option for that system requirement. However, the fourth system configuration showed that configuring the microgrid with solar PV and battery energy storage only was the most expensive option of all the other microgrid configurations with the NPC and COE of 363,593 $ and 0.492 $/kWh respectively. The reason for that was that the configuration required a bigger battery bank of 300 kWh to ensure uninterrupted supply meanwhile the battery constitute the most expensive component of the microgrid. To reduce the need for a larger battery bank, a 13 kW biogas generator was introduced to the system, reducing the battery bank from 300 kWh to 100 kWh, therefore, reducing the system's NPC and COE to 206,664 $ and 0.318 $/kWh respectively.

- **How will the microgrid system provide sustainable electric energy in the DRC?**

To achieve the sustainability of renewable energy-based microgrids, the system should consider direct power consumption from the community to be supplied and foresee an increase in consumption. However, considering the potential increase in the load requirement leads to an increase in system costs as the microgrid should be sized accordingly. As one of the countries with the lowest average electricity tariff in the SSA region (Power Africa, 2019), developing a microgrid that meets the present and potential future electricity requirements while matching the existing tariff in the DRC is a challenge. The tariff structure represents a balance between meeting the need of the government, developers, and customers. To be able to keep that balance in the DRC, the following approach should be observed: The public can be charged the same rate they would be charged by connecting them to the grid or the rates that they are already subject to, however, given that the electricity from solar microgrid would generally come at a higher cost than the one from the grid or existing ones, the entities in charge or government should revise policies to account for subsidies which allow meeting cost requirement the developers set to recover their cost.

## 6.2. General conclusion

The low electricity access rate in SSA is an ongoing issue. The majority of the region's population, especially in remote areas, do not have reliable electricity access and one of the major reasons identified was the complexity and high cost associated with the extension of the existing grid. In this research study, the focus was on the DRC, which has one of the lowest electricity access in the SSA region. Like many other countries in the region, DRC's existing grid infrastructures are fragmented and only operate at half their capacity, leaving more than 75% of the population, of which 90% live in remote areas, without electricity access (Power Africa, 2019). Different studies have shown that the use of isolated microgrid systems with renewable energy sources can be used to provide electricity access to remote communities of SSA countries such as DRC. Given the availability of solar energy resources in the DRC, this study focused on configuring the microgrid with solar PV as the energy source.

A comprehensive literature review was conducted on solar PV technology, microgrid, and energy storage system to get an overview of their configurations and their operating mechanism. While looking at solar PV, different technologies were presented and the DRC solar PV potential was also highlighted to underline the feasibility of solar PV microgrids in the country. While looking at the microgrid technology, the focus was on its operation and distribution, and after looking at those two aspects, a review was conducted on the DRC microgrid potential, the government policy around it, and the country's regulatory environment regarding microgrid systems. After looking at the solar PV and microgrid technologies, different energy storage technologies that could be integrated into the microgrid architecture were also discussed to get an overview of the configuration and integration.

When designing a solar PV-based microgrid, the most suitable location is a location with considerable solar penetration. Although in this study Kongolo was the main location selected for the implementation of the microgrid, five additional locations with considerable solar penetration were also considered namely Butembo, Gbadolite, Bolomba, Mweka, and Kolwezi. All the locations considered in this study were 20 km away from the existing grid. The total number of households to be supplied by the microgrid was 200 and that was split into the groups of 100, 60, and 40 based on the low-income, medium-income, and high-income categories respectively. The different household categories were used to determine the quantities and ownership of the community electrical appliances ownership of the household which ultimately determined the total load requirement of the microgrid which was 138.92 kWh per day.

The model of the microgrid started with a preliminary sizing on PVSyst. The obtained load requirement was first used as input to the software to preliminarily size the system. The preliminary microgrid configuration results consisted of 35 kWp of solar PV and 320 kWh of battery energy storage. After the preliminary sizing on PVSyst, the obtained results were used as a reference to model the microgrid on HOMER Pro. The modeling on HOMER Pro considered five different configurations namely the solar PV configuration, solar PV with diesel generator configuration, diesel generator configuration, solar PV with battery energy storage configuration, solar PV with battery energy storage, and diesel generator configuration. The results of each system configuration were analyzed thoroughly and the most suitable microgrid configuration had to provide the lowest NPC, COE, and the grid break-even distance below 20 km. After analyzing each configuration, the simulation results showed that the most suitable microgrid configuration consisted of 41.7

kW of solar PV, 100 kWh of battery energy storage, and 13 kW of biogas generator. The configuration could provide sustainable electricity access to the town of Kongolo at the lowest NPC of $206,664 and COE of 0.318 $/kWh. The microgrid configuration also had a grid break-even distance of 15.26km, indicating that the microgrid could be well-considered instead of extending the microgrid to electrify the town as the nearest connection point to the grid was more than 20 km away.

The microgrid configured with solar PV, battery energy storage, and diesel generator was also used to supply the other five towns considered in the study. The load requirement of all the communities was kept similar to the one of Kongolo and the results of each simulation showed that the microgrid configuration could sustainably electrify each community with the highest NPC and COE being $224,303 and 0.345 $/kWh respectively. The grid break-even distance was also not more than 16.52 km away making the isolated microgrid the most suitable solution for each community compared to grid extension.

Given that the availability of electricity will probably arouse the procurement of more electrical appliances, sensitivity analysis was conducted to determine the impact of the increase in load requirement on the microgrid configuration and costs. The analysis results showed that a 25% load increase will change the microgrid components to 52.7 kW solar PV, 13 kW of Biogas generator, and 300 kWh of battery energy storage will result in the increase of the NPC and COE to $302,356 and 0.372 $/kWh respectively. Whilst comparing it with the possibility of extending the grid to the community, this microgrid configuration still presents a more viable electrical network for the town compared to the grid extension as the grid break-even distance is just above 20 km as shown in Figure 51. However, the analysis results also showed that in case of a 50% load increase, a grid extension could present a more viable system to electrify the community as the grid break-even distance of microgrid configuration is more than 30 km.

## 6.3. Recommendations for future work/Future work

Although the solar PV microgrid plus battery energy storage system and biogas generator modeled in this study provided a sustainable electricity network for the remote locations in the DRC, the exploitation of a different energy storage system can still be considered. DRC possesses a considerable potential for hydroelectric energy which can be used as an energy storage system for the microgrid. Although the increase in the use of battery energy storage systems might lead to a price decrease in the years to come, the development and use of locally available resources will probably present a much cheaper option for the country. Also given that the modeled microgrid will most probably use more than one energy source, it would be valuable to look at the development of an Energy Management System which possesses the intelligence to execute different energy management operations such as energy arbitrage and multiple source control optimization.

More than 90% of the DRC population that does not have electricity access lives in remote locations with no access to the grid. The situation will lead to more microgrid development and as observed in this study, all the developed microgrids presented a more viable solution compared to the grid extension. However, population growth and change in demand might require the ease of scalability or expansion of the microgrid (Shahzad *et al.*, 2023).

The intermittent nature of renewable energy sources used for the microgrid can create multiple issues such as voltage and frequency fluctuations. Given that the largest part of the DRC population might be making use of renewable energy-based microgrids for their electrification, their resilience, and reliability can be improved by looking at the multi-microgrid system (MMG) configuration. This configuration can be used to not only improve the resilience of each microgrid, but it can also improve the utilization of renewable energy as well as the costs associated with it (Saha *et al.*, 2023).

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