Cape Peninsula
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SOCIO-ECONOMIC ANALYSIS AND BENEFITS OF A SUSTAINABLE MICRO-GRID FOR RURAL COMMUNITIES

by

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ABSTRACT

The availability of dependable and environmentally friendly electricity is crucial to socioeconomic growth, particularly in rural areas. Pursuing inventive and economical energy solutions in these regions is an essential undertaking that holds significant consequences for the welfare and prosperity of the local populace. This technical research examines a sustainable microgrid's advantages and socioeconomic effects in a rural area, particularly in the Kikwit community.

This study compares two different energy systems: a diesel generator that stands alone and a hybrid microgrid that combines solar photovoltaic (PV) panels, energy storage, and a diesel generator. The assessment of these systems goes beyond a simple financial study and considers factors such as long-term socio-economic effects, dependability of the electrical supply, and environmental sustainability.

The outcomes of meticulous examination and simulations support the hybrid microgrid approach. This integrated system outperforms the standalone diesel generator regarding environmental stewardship and power output and showcases greater economic viability. Its comprehensive and progressive strategy promises the Kikwit community substantial socioeconomic development.

With a thorough analysis of the study's methodology, main conclusions, and implications, this research thoroughly evaluates the potential for sustainable microgrids to improve and empower rural communities. It emphasizes how crucial sustainable energy solutions are on a larger scale when considering rural development, environmental stewardship, and the goal of a more sustainable and just future.

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Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

1.1) BACKGROUND OF THE STUDY

Rural electrification seems to be a problem many developing countries are faced with. The micro-grid concept, therefore, proves to be the solution to this ongoing problem. Integrating storage devices with micro-grids allows the micro-grid to be easily modified and improves the efficiency[1,2].

Due to the high cost of extending the electricity grid, considering capital costs and transmission and distribution losses, remote rural communities often have no access to electricity. The alternative could be to make use of a micro-grid [3].

Micro-grids are modern small-scale versions of the centralised electrical system. Microgrids ensure reliability, carbon emission reduction, diversification of energy sources and cost reduction. It can ensure that areas without any electrical infrastructure are allowed access to reliable electricity and has become known as a flexible architecture for using distributed energy resources to meet the needs of various communities. Micro-grids, just like the primary power grid, generate, distribute and control the flow of electricity to consumers but do so locally. This could be the perfect way to integrate renewable resources at the community level, thus allowing for customer participation in the electricity enterprise [4,5].

Integrating distributed generators, such as solar PV, wind turbines and/or diesel generators, to create a micro-grid could be the solution to electrifying these rural communities.

1.2) STATEMENT OF RESEARCH PROBLEM

Access to electricity has such enormous potential to improve the lives of people that even the slightest increase in electricity being made available could generate considerable socio-economic benefits. However, the benefits and challenges of implementing a micro-grid in a rural community need to be analysed to determine if this alternative method of fulfilling the electricity needs of a rural community is the solution. Therefore, this research project discusses the need for a rural community to have access to electricity and how this impacts the community.

Will the benefits of implementing a micro-grid to fulfil the need for electricity in a rural community outweigh the challenges

1.3) AIMS AND OBJECTIVES OF RESEARCH

This research project aimed to simulate the implementation of the micro-grid concept to allow rural communities access to electricity and determine if this micro-grid is a sustainable solution.

- To determine which renewable energy sources to integrate for the micro-grid.
- Determine the size of the micro-grid

- Simulate the microgrid to decide if it is sufficient and sustainable.
- Compare results obtained from the simulation to determine if the micro-grid is feasible.
- Discuss options to make the micro-grid sustainable.
- Discuss and Compare the socio-economic advantages and disadvantages of access to energy in rural communities.

1.4) RESEARCH DESIGN AND METHODOLOGY

This research comprised investigation methods related to design and simulation techniques using HOMER Energy software. Mathematical modelling was used to present the results obtained from the simulations.

This was achieved with the following requirements:

- A comprehensive literature study was conducted on the following:
  - Literature review on rural electrification and the impact it has on rural communities.
  - Literature review on micro-grid systems and the feasibility of implementation in rural communities.
  - Literature review on low voltage network planning.

- A case study was proposed whereby a rural distribution network was modelled and analysed using HOMER Energy software.

- Requirements for the Design and Simulation Phase of the case study:

  - The rural living standard measure (LSM) was determined according to NRS standards and specifications.
  - Input parameters for the software simulation were determined.
  - The number of households the micro-grid was to supply was determined.
  - The average electricity usage of an average rural household was determined.
  - The combined electricity load was calculated.
  - Load data determined in previous steps was utilised to size the micro-grid and all accompanying components of the micro-grid.
  - Data obtained was input into software, and simulations were run.
  - Results from the simulations were obtained and represented using mathematical modelling. (Charts, graphs, etc.)
  - The results obtained were analysed, compared and discussed to determine whether or not the micro-grid would be feasible to implement.

1.5) OUTCOMES OF RESEARCH

The expected outcome of this research is to design and simulate a micro-grid system that will be financially feasible and sustainable for implementation in rural communities

that lack access to electricity and, by doing so, to improve the socio-economic development of these communities.
This research is expected to contribute a sustainable solution to the problem of energy poverty in rural communities.

CHAPTER 2: LITERATURE REVIEW

2.1) SOCIO-ECONOMIC IMPACTS OF ENERGY ACCESS

2.1.1) Introduction

Energy access refers to an individual's or community's ability to get and use dependable, affordable, and sustainable energy for fundamental needs. It includes modern energy services that serve fundamental activities such as lighting, cooking, heating, cooling, communication, and productive applications such as commercial operations or agricultural power generation. Access to energy is crucial in tackling a variety of socioeconomic difficulties since it supports economic growth, increases agricultural output, improves healthcare, and fosters educational achievement, among other advantages. This section investigates the socioeconomic consequences of energy access, concentrating on job creation, healthcare, education, women's empowerment, and community development [6].

The next subheadings will go into additional detail about these main socioeconomic issues.

Job Creation and Economic Opportunities

Energy access in rural areas promotes economic growth by encouraging the establishment and expansion of businesses. This results in job creation across various sectors, ranging from agriculture to small-scale industries, and contributes to increased community income levels [7]. Access to energy enables people to start and run businesses, which is particularly significant in rural areas where electricity allows for the operation of small businesses such as local shops, food processing units, and craft workshops [8,9].

Increased Agricultural Productivity

The use of electrically powered equipment and irrigation systems facilitates the adoption of modern farming practices, increasing agricultural productivity, reducing manual labor, and improving overall farm efficiency [7]. With reliable energy access, farmers can experiment with new crops and farming techniques, leading to improved food security and income generation opportunities through high-value crop cultivation and agro-processing [10].

Healthcare Progress

Energy access is critical for healthcare facilities as it enables the operation of medical equipment, vaccine refrigeration, and surgery lighting, resulting in improved healthcare services, lower mortality rates, and overall community health [8]. Furthermore, communities with access to energy can benefit from telemedicine services, allowing remote consultations with healthcare professionals, which is particularly beneficial in rural areas where healthcare facilities are scarce [7,8].

Education and Professional Development

Energy access contributes to education by providing lighting for schools and homes, allowing students to study longer, which improves educational outcomes and opens up opportunities for skill development, contributing to long-term socioeconomic development [7], [8]. Additionally, the availability of electricity facilitates access to information via electronic devices and the internet, broadening educational horizons and enabling people to learn new skills and stay updated on global developments [10].

Women's Empowerment

Energy access can empower women by enabling them to engage in income-generating activities such as small-scale businesses or craftwork, promoting financial independence and gender equality, thereby strengthening the community's socioeconomic fabric. Reliable electricity also improves access to education for women and girls, allowing them to attend evening classes and use electronic learning resources, breaking the cycle of poverty and furthering gender equality [7,8].

Connectivity in the Community

Access to energy enhances communication within and outside the community through the use of mobile phones, internet access, and other communication tools, facilitating information sharing, coordination, and community development initiatives [7], [8]. Improved connectivity allows rural communities to sell their products in larger markets, connecting farmers with buyers and expanding the reach of local businesses, thereby increasing economic opportunities [7,8,10].

Mitigation of Rural-Urban Migration

Energy access enables the creation of local, sustainable livelihoods, reducing the need for rural residents to migrate to urban areas in search of work, which helps maintain the social fabric of rural communities. It also promotes balanced regional development by fostering economic activity in rural areas, reducing population and resource concentration in urban centers and enabling a more equitable distribution of opportunities [9].

2.2) RURAL ELECTRIFICATION

2.2.1) Introduction

Rural electrification is important for sustainable development because it improves living conditions, fosters economic expansion, and advances social well-being in neglected areas. Despite its importance, many rural populations, particularly in developing nations, continue to lack dependable access to electricity. To acquire insight into the difficulties, advantages, and methods for closing the power gap in rural regions, this literature review will explore the existing research and academic works on rural electrification. [6,7,8]

2.2.2) The importance of rural electrification

The ability to get electricity is critical to social and economic advancement. It is essential for many facets of life, including entrepreneurship, healthcare, agriculture, and education. Governments and policymakers may empower people, combat poverty, and advance the achievement of the Sustainable Development Goals by introducing electricity to rural regions [11,12].

2.2.3) The Relationship between Socioeconomic benefits and access to electricity

The relationship between electricity access and socioeconomic benefits is significant, as access to reliable and affordable electricity can have a transformative impact on various aspects of a society's well-being and economic development [13]. Here are key ways in which electricity access contributes to socioeconomic benefits:

For first of all, reliable energy availability is essential for powering businesses, farms, and other operations. It boosts output by making machinery, tools, and technology more accessible, supporting economic growth by improving manufacturing efficiency.

Second, industries and businesses having access to electricity can increase their operations, leading in job growth. Furthermore, access to electricity promotes the development of new economic activity, encourages entrepreneurship, and provides income-generating opportunities for people and communities.

Thirdly, electricity is required to power healthcare facilities. Hospitals and clinics may run medical equipment, store vaccinations and pharmaceuticals, and improve lighting for medical operations. This improves the quality of healthcare services and benefits the general public health.

Furthermore, electricity promotes educational activity by powering schools, computer labs, and instructional technology. Students benefit from greater study lighting, while professors can use multimedia resources. Furthermore, access to power facilitates connection, allowing individuals to obtain information via the internet and other communication channels.

Access to electricity in rural areas may boost growth by enabling agricultural operations, agro-processing, and small-scale enterprises. It may also improve people's quality of life by lighting up their houses, increasing the amount of productive hours throughout the day [14].

Electricity improves people's quality of life by providing lighting, warmth, and cooling in their houses. It improves comfort, security, and overall well-being while reducing reliance on traditional, often harmful energy sources [14].

Electricity is an important driver of technological growth. It encourages R&D, innovation, and the adoption of new technologies, all of which contribute to global economic diversity and competitiveness [15].

Furthermore, access to electricity can increase gender equality by relieving the pressure on women and girls who may be responsible for home activities that are made simpler with electricity. It also enables women to pursue income-generating activities and launch their own enterprises [15].

Electricity is commonly utilized to promote urbanization and infrastructural development. It encourages investment, the establishment of industries, and the expansion of urban regions.

Finally, access to electricity may promote the adoption of cleaner, more sustainable energy sources, so contributing to environmental sustainability and mitigating the environmental effect of existing energy sources.

To summarize, access to electricity is critical to unleashing socioeconomic advantages by increasing economic activity, providing essential services, and improving individuals' and communities' overall quality of life. As a result, initiatives to expand access to electricity are frequently seen as a critical component of long-term development strategy.

2.2.4) Socioeconomic difficulties in The Democratic Republic of Congo

The Democratic Republic of the Congo (DRC) has several complicated socioeconomic difficulties that influence the country's well-being and progress. These issues are intertwined and frequently impacted by historical, political, and economic considerations [16,17]. The following are the DRC's significant socioeconomic challenges:

Poverty is a serious concern, with a large proportion of the DRC's people living in deplorable conditions. This pervasive poverty is frequently accompanied with limited economic prospects, restricted access to education and healthcare, and unequal wealth distribution.

Political instability and violence have significantly influenced the DRC's socioeconomic environment. Persistent political insecurity and historical conflicts hinder economic operations, displacing communities and perpetuating the poverty cycle.

Corruption and governance concerns are widespread in the DRC, impacting numerous areas such as government, business, and public services. Weak governance structures and institutions promote corruption, impede effective development methods, and worsen inequality.

The Democratic Republic of the Congo's education system has major obstacles, including poor infrastructure, a dearth of competent instructors, and restricted access to distant areas. These concerns contribute to lower literacy rates and impede human capital development.

Healthcare service in the DRC has several challenges, including poor infrastructure and the presence of illnesses such as malaria. Recent health crises have exacerbated inequality, making it harder to offer basic healthcare services to the community.

Inadequate infrastructure, including roads, energy, and telecommunications, stifles economic growth. The absence of dependable transportation and energy sources hampers economic operations and access to key services.

The DRC's economy is primarily reliant on natural resources including cobalt, copper, and coltan. However, this dependency puts the economy subject to variations in global commodity prices, causing economic instability.

Wealth disparity is widespread in the DRC, with certain areas and groups profiting disproportionately from economic activity and resource exploitation. This gap in wealth relates to variations in living conditions and opportunities.

Human rights breaches are frequently related to continuous wars and political instability, complicating attempts to safeguard the population's safety and well-being. These abuses include violence and relocation.

A shortage of work possibilities, particularly in the formal sector, results in high rates of unemployment and underemployment. This economic dilemma is typically associated with bigger difficulties such as political instability and a lack of economic diversity.

Environmental deterioration is a major problem in the DRC. The use of natural resources, frequently without sustainable techniques, causes environmental degradation, impacting agriculture, ecosystems, and overall ecological sustainability.

Addressing the DRC's socioeconomic issues will need a comprehensive and coordinated approach that includes measures to enhance governance, invest in education and healthcare, encourage economic diversification, and address the core causes of war. International cooperation and support are also critical in assisting the DRC in overcoming these obstacles and achieving sustainable development.

2.2.5) Challenges in rural electrification, specifically in The Democratic Republic of Africa

Technical Challenges

The lack of existing infrastructure in rural areas, such as roads and power grids, makes electrification difficult and costly. Difficult geographical terrains (mountains, forests, etc.) and extreme weather conditions increase the expense and complexity of installing electrical networks [19,20].

Financial Constraints

Infrastructure expansion, which includes transmission line extensions and substation building, requires a significant upfront capital commitment. Rural populations have low incomes, making it difficult to recover expenditures, especially with high connection fees and tariffs [20,21].

Regulatory Issues:

Inconsistent or overly bureaucratic regulatory frameworks can cause uncertainty and discourage private-sector investment. Political instability and weak governance institutions in some areas make it difficult to implement and sustain electrification programs [17,22].

Community Acceptance:

A lack of community engagement and information regarding electrification projects can lead to opposition, delaying or derailing them.Reluctance to accept new technology may be influenced by cultural factors and existing energy usage patterns [19].

While progress has been achieved, rural electrification difficulties in the Democratic Republic of the Congo remain complicated and multifaceted. Overcoming these difficulties necessitates continual efforts, stakeholder collaboration, and an emphasis on innovative and sustainable solutions adapted to the country's unique rural surroundings.

Africa's rural electrification difficulties are equally complicated, necessitating comprehensive solutions. Successfully addressing these concerns requires effective coordination among governments, international organizations, the commercial sector, and local communities. Accelerating rural electrification initiatives may increase economic growth, improve healthcare and education, and alleviate energy poverty in rural areas. Innovative finance structures, regulatory reforms, and the use of renewable energy sources can all help with these efforts.

2.2.6) Grid Connection Difficulties and Rising Population Numbers in The Democratic Republic of Congo

Rising household numbers and grid connection costs provide significant impediments to universal electrification in the Democratic Republic of the Congo (DRC). The population has grown significantly over the years, resulting in an increasing number of houses using energy [16]. As the population grows, so does the need for power in houses. This situation is compounded by urbanization, as people move from rural to urban areas, increasing the need for energy in urban households. This mobility complicates the delivery of power to rapidly rising urban populations.

Furthermore, the DRC has substantial infrastructural difficulties that inhibit electricity attempts. The country's difficult topography and great distances between populous regions make building and maintaining a large-scale energy infrastructure expensive. Connecting distant and rural areas to the national grid is sometimes more expensive than connecting metropolitan areas due to the need for substantial transmission and distribution systems. Economic issues exacerbate the dilemma, since the expenses of expanding the grid to sparsely populated or economically disadvantaged areas may be disproportionately expensive relative to the potential revenues from these areas, posing financial challenges for utilities [23].

Implications and Challenges:

Financial constraints have a substantial influence on the capacity to connect a rapidly increasing number of houses to the grid, stressing utility companies' resources. Limited financial resources may limit the development of critical energy infrastructure. High grid connection costs can aggravate disparities in power availability between urban and rural areas. Because of economic considerations, metropolitan areas may receive priority for energy, leaving rural and remote places neglected. This access disparity is a big problem because it perpetuates the cycle of poverty and limits development potential in less accessible areas. [23,24]

The growing cost of grid connections may encourage the development of off-grid and decentralized renewable energy sources. These strategies may be less expensive for servicing remote or difficult-to-reach populations. Effective infrastructure planning is critical for managing the rising number of homes and ensuring that grid expansion projects are strategically deployed to maximize their impact. Financial incentives and help from the government and other stakeholders may be required to encourage private participation in electrification projects, especially in locations with high connection costs. [25]

Involving local communities in the electrification process may foster a sense of ownership, resulting in more cost-effective and long-lasting solutions. Community engagement may also help develop regionally suitable technological and energy solutions, ensuring that the deployed systems are long-lasting and well-maintained. By resolving these problems and pursuing alternate alternatives, the DRC may make major strides toward universal electricity and socioeconomic growth.

Strategy Options:

Prioritization and progressive techniques are critical in electrification projects, which should include population density, economic feasibility, and social consequences. Projects can be divided into phases to assist manage expenditures more efficiently, ensuring that the most vital areas are addressed first. Technology innovation is also an important consideration. It is critical to investigate innovative technologies and construction methods that will reduce the cost of extending the electrical system. This involves looking at more cost-effective materials, construction procedures, and intelligent grid technologies to improve efficiency and save prices. [26]

Public-Private Partnerships (PPPs) are important in this scenario. Encouraging public-private partnerships can help share the financial burden and expertise required for grid expansion. These collaborations can attract private investment while also encouraging good project management, resulting in more successful and sustainable electrification programs. A mix-mode electricity strategy should also be studied. This hybrid approach, which combines grid extension with off-grid and distributed choices, provides greater flexibility in meeting the demands of diverse and dispersed populations, ensuring that even the most isolated places get dependable energy. [27,28]

Financial aid for low-income families is another important consideration. Implementing financial support methods or subsidies can help low-income families gain access to power, alleviate cost concerns, and ensure that everyone benefits from electrification initiatives. Overall, by implementing these techniques, the Democratic Republic of the Congo may make great progress toward universal electrification, therefore enhancing the quality of life for its population and supporting economic growth. [29]

A comprehensive and flexible solution is required to address the difficulties of expanding household numbers and escalating grid connection prices in the DRC. It entails strategic planning, new technology, community participation, and public-private sector collaboration. Furthermore, continuous monitoring and evaluation are necessary to assess the performance of electrification projects and make informed changes as needed.

2.2.7) Approaches to Rural Electrification

Numerous strategies have been developed and implemented globally to address the difficulties connected with rural electrification. Grid extension is a popular strategy that extends electrical cables to reach isolated places. This strategy may be expensive and logistically challenging in areas with poor infrastructure and low population density. [30]

Off-grid alternatives include freestanding solar systems, mini-grids, and distributed renewable energy sources. Due to their scalability, affordability, and minimal environmental effects, these off-grid methods have become more prevalent in recent years. They have successfully brought power to rural areas, supported socioeconomic growth, and increased energy resilience in outlying locations. [30]

2.2.8) Benefits of Rural Electrification

There are several advantages to electrifying rural places. Through medical equipment, refrigeration of vaccinations, and reliable power for medical facilities, access to electricity makes it possible to provide better healthcare services. It also supports education by providing illumination for studying, enabling online learning, and powering computers and other educational tools. [31]

Rural electricity also encourages economic growth by fostering entrepreneurship, assisting small enterprises, and luring investors. Electric pumps are used for irrigation, agricultural goods are refrigerated, and processing capacities are boosted with access to power. Additionally, electrification lessens dependency on conventional fuels, positively impacting the environment by lowering carbon emissions and improving air quality. [32]

2.2.9) Rural Electrification Initiatives in The Democratic Republic of Congo

Many nations have opted for renewable energy sources to generate both long-term and short-term energy to attain cheap and clean energy, Goal #7 of the UN Sustainable Development Goals (SDG). Despite the directive's lack of legal force, developing nations have embraced solar PV technology on big and small sizes to offer a sustainable power source. The enormous rise in solar photovoltaic (PV) and wind energy technology in recent years is proof of this. Installed renewable capacity expanded by 2.4 TW at the end of 2018, outpacing fossil fuel and nuclear power combined with solar PV and wind power, contributing 55% and 28% of the total capacity, respectively. [21,22]

Solar PV technology in decentralized solar power systems is advantageous in many developing nations for supplying economical and clean electricity in remote or rural unconnected regions. Energy poverty is a significant global issue, according to [35], especially in emerging nations like some parts of Asia and Africa. According to the authors, the most affected are rural families in these areas, whose inhabitants are forced to utilize conventional biomass and fossil fuels for cooking and lighting. Energy is essential for socioeconomic advancement and higher living conditions in the aforementioned locations, according to [36]. The authors emphasized how energy poverty and the deterioration of coal-fired power plants are being made worse by the rising cost of fossil fuel energy in many developing nations. Solar household systems (SHSs) have been used to achieve this and ensure inexpensive and clean energy access for all people. Some off-grid solar energy electrification initiatives are shown in Table 1 for a few Sub-Saharan African nations.

Energy poverty in Sub-Saharan Africa has given off-grid business owners on the continent a substantial market potential, as seen in Table 1. Off-grid suppliers used the inadequate energy infrastructure and the slow rate of electrification in rural regions to their advantage to grow their business. East African nations, including Kenya, Tanzania, and Uganda, have given birth to many of the continent's off-grid business owners, with Kenya having the highest concentration. [37] reports that 66% of the SHSs and pico-solar systems sold in Africa in 2015 occurred in these nations. However, it is essential to highlight that the rising popularity of off-grid electricity in East African countries does not necessarily mean they have the lowest rural electrification rates. Less than 10% of the people in the Central African Republic, Chad, and Sierra Leone had access to modern electricity between 2000 and 2016, according to the International Electricity Agency's (IEA) 2017 Energy Access Outlook report [38].

Table 1: Sub-Saharan Africa Solar Electrification Schemes [39]

SERVICE PROVIDER	COUNTRY	DESCRIPTION
Zola OGE	*Tanzania*	Zola off-grid electricity delivers pay-as-you-go SHS for USD 0.19 a day utilizing the mobile payment method, even though between 80% and 90% of Tanzanians lack access to modern energy. The services are intended for the most vulnerable and include basic household necessities like indoor lighting and mobile phone charging [28,29].
PEG Africa	*Ghana & Ivory cost*	The top pay-as-you-go off-grid business in West Africa is PEG. Thanks to a Ghanaian enterprise, over 500,000 isolated and rural households in West Africa are now connected to solar energy technology [42].
Devergy	*Tanzania & Ghana*	Devergy offers smart, off-grid rural electricity. The undersized SHS has been highlighted by the energy service company (ESCO) as one of the obstacles preventing consumers from using the system since their demand is not being satisfied. Devergy offers a micro-grid system with intelligent remote components operating at 24 VDC (250 W). The SHS is monitored remotely around the clock and works on adoption capacity. As a result, the solar grid is enlarged as necessary as the demand for household electricity increases [43].
Millennium Village Project (MVP)	*Ghana, Nigeria, Mali, Senegal, Malawi,*	As a prototype initiative towards the MDGs, the Millennium Village initiative (MVP) was started in 2004 in Bar Sauri, Kenya. The initiative

	Tanzania, Rwanda, Kenya, Uganda, and Ethiopia	expanded to include 14 settlements in 10 more Sub-Saharan African nations. MVP established distribution schemes for portable, solar, rechargeable LED lanterns, typically with lights and 1 Wp solar modules to fulfil low-wattage home power needs. The lanterns are bought off the shelf from nearby sellers, who then get more lanterns after paying back the remaining amount after deducting their profits [44].
Powerhive	*Kenya*	In 2012, a pay-as-you-go solar energy firm began a 1.5 kW microgrid system trial project for a Kenyan community called Mokomoi. Customers may use the system to charge their mobile phones, radios, televisions, and indoor and outdoor lighting. Powerhive is serving more than 1500 individuals in numerous Kenyan settlements. The Kenyan government has backed the effort by giving Powerhive a concession to run as Kenya's first private utility firm [33,34,35].
OOLU	*Senegal, Mali, Burkina Faso and Nigeria*	Off-grid solar energy provider OOLU was established in Senegal in 2012. Since then, more than 35,000 pay-as-you-go SHSs have been sold, and the company now operates in four nations in West Africa.
SharedSolar	*Senegal, Mali and Uganda*	In isolated villages without power, SharedSolar offers pay-as-you-go electricity to households and small businesses. Because prices are based on the time of usage and installed capacity of their choice, customers' invoicing is based on affordability. Similar to the Devergy operation model, SharedSolar has a variable SHS architecture, meaning that its generating and storage capacity are tailored to the needs of individual households. Capacity is expanded upon request as demand rises [30,36].
ARESS	*Benin*	The installation and distribution of solar energy technology are the focus of the ESCO ARESS, situated in Benin. The firm developed the pay-as-you-go business model for remote rural residents in the nation from a pico to a mini-grid system [49].
M-Kopa	*Tanzania, Uganda, and Kenya*	M-Kopa, established in 2011, uses pay-as-you-go and lease-to-own finance strategies to provide off-grid energy to unconnected families in East Africa. More than 200,000 households in the area receive off-grid energy from the firm for their lighting, radios, cell phone chargers, televisions, and refrigerators. According to many studies, installed SHS capacity varies and is influenced by household affordability [38,39].
Fenix power system	*Nigeria, Benin, Zambia, Mozambique, Uganda and Ivory Coast*	Fenix offers off-grid solar power on a lease-to-own model. Its SHS comprises solar PV modules and an intelligent battery system that can handle different loads depending on the needs of families. To fully own a product, customers must make regular payments via a mobile money platform over 12 to 36 months [52].
Easy Solar	*Sierra Leone*	Pay-as-you-go off-grid startup Easy Solar. They provide a variety of solar technology, including solar lamps, home lighting systems, and appliances.

2.3) MICROGRIDS

2.3.1) Introduction

Microgrids are a dynamic field in which numerous models have been developed to satisfy the distinct energy needs of local communities. Understanding grid types, investigating successful case studies, and analyzing lessons learned from existing models provide significant insights into micro-grid implementations' many uses and consequences.

2.3.2) Types of Microgrids

Grid Types

AC Microgrids

Alternating Current (AC) micro-grids are more widespread and resemble traditional power systems. They use alternating current for generation and distribution and are ideal for more extensive, linked systems. They enable the use of ordinary electrical devices without requiring conversion.[44,45]

AC microgrids are designed to emulate the structure and performance of traditional power systems. Because they are comparable, they can be easily integrated into current electrical grids, allowing for a seamless transition to decentralized energy solutions without significant changes. It uses alternating current not only for distribution but also for generating electricity. This characteristic is consistent with typical utility-scale power generation practice, making AC microgrids a familiar and adaptable option for engineers and operators. [44,45]

AC microgrids are especially well-suited for applications where power requirements transcend beyond localized, small-scale needs due to their design. These systems are scalable, allowing for the incorporation of different energy sources as well as the energy demands of interconnected networks. One of the most significant advantages of AC micro-grids is their compatibility with standard electrical devices. Because most appliances and machinery operate on alternating current, AC micro-grids eliminate the need for additional conversion equipment. This compatibility simplifies the adoption of micro-grid technology and ensures a smooth transition for end users. [44,45]

Benefits of AC Micro-Grids:

Interoperability:
AC microgrids improve interoperability by conforming to the prevalent alternating current standard. This ensures they are compatible with a wide range of electrical devices, making them more accessible and user-friendly. [44,45]

Large-Scale Renewable Integration Facilitation:
AC micro-grids are ideal for incorporating large-scale renewable energy sources into the grid. Alternating current is easily converted to higher or lower voltages, allowing for the efficient transmission of power generated by various renewable sources. [44,45]

Integration Ease:
The similarity of AC microgrids to traditional power systems facilitates integration. This is especially useful when retrofitting existing infrastructure or expanding energy networks in cities and suburbs. [44,45]

Conclusion

In conclusion, AC microgrids are a practical and widely used solution for decentralized energy distribution, particularly in scenarios involving larger, interconnected systems. Their compatibility with standard electrical devices and traditional power systems contributes to their popularity and effectiveness in various energy applications.

DC Microgrids

Direct Current (DC) micro-grids are becoming increasingly popular, especially in niche applications such as off-grid renewable energy systems. In contrast to more traditional Alternating Current (AC) micro-grids, DC microgrids only use direct current. Their growing popularity is due to their efficiency in integrating renewable energy sources, specifically those that generate and store electricity in direct current (DC), such as solar panels and batteries.[55]

DC microgrids only use direct current for electricity generation and distribution. This departure from traditional alternating current power systems contributes to their specialized application, particularly in contexts where DC-native technologies play a significant role. They are especially effective at incorporating renewable energy sources like solar panels and batteries. DC microgrids eliminate the need for conversion processes because they generate and store electricity through direct current. This reduces energy losses and improves overall system efficiency. [55]

Direct current exclusively simplifies the design and operation of DC microgrids. Because complex conversion equipment is no longer required, these microgrids are more accessible to implement, maintain, and expand. [55]

DC microgrids are best suited for off-grid applications where conventional power infrastructure is unavailable. They are well-suited for remote areas because of their efficiency in directly harnessing power from renewable sources, providing sustainable and reliable energy solutions. [55]

Benefits of DC Microgrids:

Increased Use of Renewable Energy:
DC microgrids are designed to work in tandem with renewable energy sources, taking advantage of the inherent characteristics of technologies such as solar panels and batteries. As a result, renewable energy is better utilized, and sustainability is improved. [55]

Energy Loss Reduction:
Because there are fewer AC-to-DC and DC-to-AC conversions, energy losses are reduced, increasing the overall efficiency of DC microgrids. This is especially useful in systems where renewable energy sources primarily generate direct current. [55]

Cost-Effectiveness:
DC microgrids are cost-effective due to their simplicity of design and lack of conversion equipment. This makes them an appealing solution, particularly in applications where budget constraints are a factor. [55]

Conclusion

In conclusion, DC microgrids are a specialized and efficient solution gaining popularity in scenarios where renewable energy integration, design simplicity, and reduced energy losses are critical. Their use in off-grid settings is particularly notable, demonstrating their adaptability and
effectiveness in providing sustainable and reliable energy solutions.

Hybrid Microgrids

By seamlessly combining multiple energy sources, hybrid micro-grids represent a dynamic and innovative approach to decentralized energy distribution. This model incorporates renewable (solar, wind, and hydro) and conventional (diesel generators) sources. Hybrid microgrids aim to maximise each energy source's strengths, resulting in increased power generation reliability and sustainability. These systems balance energy production and demand, resulting in a reliable and continuous power supply. [44,45,46]

Hybrid microgrids are distinguished by their ability to integrate various energy sources. This includes renewable and conventional energy sources such as solar panels, wind turbines, and hydroelectric systems. This variety ensures a consistent power supply in a variety of environmental conditions. Hybrid microgrids contribute to sustainability and environmental conservation by incorporating renewable energy sources. The system maximizes the potential of solar, wind, and hydro power by harvesting energy when conditions are favourable and storing excess energy for periods of higher demand or lower renewable output. These microgrids incorporate traditional sources such as diesel generators to improve reliability and provide continuous power. During low renewable energy production periods, these generators serve as a reliable backup, ensuring a consistent power supply even in adverse weather conditions or when renewable sources are insufficient. Energy storage solutions, such as batteries, are frequently used in hybrid microgrids to store excess energy generated during peak renewable production. These stored reserves can be used during times of high demand or when renewable sources are not actively producing electricity, helping to maintain grid stability. [44,45,46]

Benefits of Hybrid Microgrids

Environmental and sustainability advantages:
Hybrid microgrids help to ensure sustainability by maximizing the use of renewable energy sources. This not only reduces reliance on fossil fuels but also reduces the environmental impact of traditional power generation. [44,45,46]

Adaptability and flexibility:
Hybrid microgrids are adaptable to a variety of energy landscapes. They can be tailored to the specific characteristics and energy requirements of various regions, making them a versatile solution for various applications, from rural electrification to industrial complexes. [44,45,46]

Increased Reliability:
The use of both renewable and conventional energy sources increases reliability. During intermittent renewable energy production periods, conventional sources can

provide a stable and continuous power supply, reducing the risk of disruptions. [44,45,46]

Energy production and demand balance optimization:
Hybrid microgrids are particularly good at balancing energy production and demand. The system intelligently switches between energy sources based on availability and demand, ensuring resource efficiency and minimizing waste. [44,45,46]

Conclusion

Finally, hybrid micro-grids are a forward-thinking solution that combines the benefits of renewable and conventional energy sources. These systems play a critical role in shaping the future of decentralized and resilient energy distribution by striking a balance between reliability, sustainability, and efficiency.

2.3.3) Case Studies

India - Husk Power Systems

<u>Technical Details</u>

Gasification of Biomass:

Rice Husk Feedstock: Husk Power Systems uses rice husks as the primary feedstock in a biomass gasification process. Rice husks are abundant agricultural residues in India, making them a viable and sustainable biomass energy source.[41,42]

Gasification Reactor: In the gasification process, rice husks are controlled combustion in a low-oxygen environment. This results in syngas, a combustible gas primarily composed of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). [41,42]

Decentralized Production:

Localised Power Plants: Husk Power Systems employs decentralized generation by setting up small-scale power plants in remote Indian villages. Each power plant is strategically placed to serve a specific region, limiting losses during transmission and maintaining efficient energy distribution. [41,42]

Gas Engines: Syngas generated by biomass gasification power gas engines. The chemical energy in the syngas is converted into mechanical energy, which drives generators to generate electricity. [41,42]

Microgrid Smart Network:

Distribution System: The electricity generated is distributed via an intelligent micro-grid network. This network consists of power lines and distribution infrastructure that connect the power plant to the village's various households and businesses. [41,42]

Microgrid Controllers: Advanced microgrid controllers control the flow of electricity, maintaining a balanced distribution and load management. These controllers utilize real-time data to enhance the microgrid's operation and maintain stability. [41,42]

Remote Monitoring: The smart microgrid is outfitted with remote monitoring systems that enable operators to monitor the system's performance remotely. This includes monitoring energy consumption, voltage levels, and any potential problems that need to be addressed. [41,42]

Improved Electricity Access:

The decentralized generation and smart microgrid network significantly enhance access to electricity in remote villages. Power generation is close to the community, minimizing transmission losses and assuring a reliable and constant power supply. [41,42]

Increased Economic Activity:

Reliable power stimulates economic activity in the community. Access to electricity facilitates the operation of small businesses, encourages entrepreneurship, and allows the use of electric appliances for various purposes, all of which contribute to economic development. [41,42]

Reduction in reliance on traditional energy sources:

Husk Power Systems helps reduce reliance on traditional, polluting energy sources by providing a cleaner, more sustainable alternative. This not only reduces environmental impact but also improves community health and well-being. [41,42]

Challenges and Solutions

Biomass Availability: Keeping a steady supply of rice husks for gasification can be difficult. Husk Power Systems addresses this by forming alliances with local farmers and implementing effective biomass collection and storage methods. [41,42]

Maintenance and Operations: Operating decentralized power plants in remote areas necessitates dealing with maintenance issues. Husk Power Systems implements rigorous training programs for local technicians and employs predictive maintenance strategies to reduce downtime. [41,42]

Conclusion

In conclusion, the technical details of Husk Power Systems in India involve a complex interplay of biomass gasification, decentralized generation, and an intelligent microgrid network. This novel approach addresses energy challenges in remote villages and has positive socioeconomic and environmental consequences.

Kenya - Powergen Renewable Energy

Technical Details

Solar Power Generation:

Solar Photovoltaic (PV) Arrays: Solar photovoltaic arrays are used by PowerGen Renewable Energy to harvest energy from the sun. These arrays are made up of solar panels that use the photovoltaic effect to convert sunlight into direct current (DC) electricity.[41,42]

Inverters: The generated direct current (DC) electricity is then routed through inverters, which convert it to alternating current (AC). Inverters are essential in making electricity compatible with the alternating current used in most household and commercial appliances. [41,42]

Microgrid Infrastructure:

Distribution Networks: PowerGen Renewable Energy designs and installs micro-grid distribution networks that effectively deliver electricity from solar power generation systems to rural households and businesses. Power lines, transformers, and control systems are all part of these distribution networks. [41,42]

Smart Meters: Smart meters are installed at each microgrid connection point. These devices allow for more precise monitoring of energy consumption, easier billing processes, and more efficient management of electricity usage. [41,42]

Micro-Grid Controllers: Advanced micro-grid controllers oversee the system's overall operation. These controllers use real-time data to optimize electricity distribution, ensure load balancing, and respond to changes in energy demand. [41,42]

Energy Storage

Energy Storage Systems: PowerGen Renewable Energy encompasses energy storage systems to address the intermittent nature of solar power. The surplus power generated during peak sunlight hours is stored in batteries, which are typically lithium-ion. The stored energy is discharged during low solar input or high demand periods. [41,42]

Battery Management Systems (BMS) monitor and control battery charging and discharging. It ensures that the batteries operate within safe parameters, extending their lifespan and improving performance. [41,42]

Remote Monitoring and Management

Remote Monitoring Systems: PowerGen Renewable Energy uses remote monitoring systems to monitor the performance of each solar-powered microgrid. These systems enable operators to remotely monitor energy production, consumption patterns, and system component health. [41,42]

Predictive Analytics: Advanced analytics, such as predictive algorithms, analyze historical data to forecast energy demand patterns. Predictive analytics aid in anticipating maintenance requirements, optimizing system performance, and improving the overall reliability of the microgrid. [41,42]

Outcomes

Increased Economic Prospects:

Dependable electricity from solar-powered microgrids fuels rural economic activity. Businesses can operate with greater effectiveness, and the availability of electricity promotes the growth of small businesses, resulting in more economic opportunities. [41,42]

Better Healthcare Services:

Reliable power makes it easier to run medical facilities. Refrigeration for vaccines, lighting for surgeries, and the use of medical equipment become feasible, resulting in improved community healthcare services. [41,42]

Extended Study Hours for Better Education:

The availability of reliable electricity extends students' study hours. Evening classes can be implemented in schools, and students can access lighting to study at home. This helps to improve education and skill development in the community. [41,42]

Community Engagement and Training

Local Capacity Building: PowerGen Renewable Energy invests in community engagement and training programs to build local capacity. Local technicians are trained to handle routine maintenance and minor issues, ensuring the micro-grid systems' long-term viability. [41,42]

User Education Programs: The community is educated on energy efficiency and the benefits of the micro-grid system. User education programs enable residents to make the most of available electricity while promoting a sustainability culture. [41,42]

Conclusion

In summary, PowerGen Renewable Energy's approach in Kenya thoroughly integrates solar power generation, microgrid infrastructure, energy storage, and advanced monitoring systems. This technical framework ensures consistent and long-term electricity access and has a positive socioeconomic and educational impact in rural areas.

United States - Kodiak Island Microgrid

<u>Technical Details</u>

Wind Power Generation

Wind Turbines: Wind turbines are a renewable energy source on Kodiak Island. These turbines convert wind kinetic energy into mechanical power, which drives generators to generate electricity.[41,42,43]

Inverters and Power Electronics: Power electronics and inverters convert wind turbines' variable and often intermittent output into a stable alternating current (AC) suitable for micro-grids. [41,42,43]

Advanced Wind Forecasting Systems: To optimize wind power utilization, the microgrid employs advanced forecasting systems that analyze meteorological data to forecast wind patterns. This enables efficient grid management and integration with alternative power sources. [41,42,43]

Hydropower Generation

Hydroelectric Generators: The microgrid draws power from nearby rivers or streams. Water is routed through turbines, which convert the potential energy of falling or flowing water into mechanical energy to power generators. [41,42,43]

Control Systems: Advanced control systems operate water flow through the turbines, maintaining maximum energy extraction from hydropower sources. These control systems are also important for grid stability and balancing. [41,42,43]

Diesel Generators

Internal Combustion Engines: Diesel generators provide dependable backup power, especially during low renewable energy production or extreme weather conditions. Internal combustion engines in generators burn diesel fuel to generate electricity. [41,42,43]

Synchronization Systems: Synchronization systems allow diesel generators to integrate seamlessly into the microgrid. These systems ensure that the diesel generators can synchronize with the existing electrical grid, ensuring stability during power transitions. [41,42,43]

Load-Following Mechanisms: Load-following mechanisms are used in diesel generators to adjust output in response to changes in energy demand. This ensures a continuous and stable power supply, especially during peak demand. [41,42,43]

Energy Storage Systems

Battery Energy Storage: The microgrid incorporates energy storage systems, typically lithium-ion batteries. These batteries store excess energy generated during high renewable output periods. Stored energy can be released when renewable production or demand is low, improving grid resilience. [41,42,43]

Grid Stabilization: Battery energy storage systems help to stabilize the grid by providing rapid energy injections or absorptions to balance sudden fluctuations in energy supply or demand. [41,42,43]

Grid Management and Control

Microgrid Controllers: sophisticated microgrid controllers manage the overall system's operation. These controllers use real-time data and algorithms to manage electricity distribution, balance loads, and ensure the microgrid's stability and reliability. [41,42,43]

SCADA: SCADA (Supervisory Control and Data Acquisition) systems allow for remote monitoring and control of the microgrid. Operators can optimize energy production and distribution by monitoring performance, analyzing data, and making real-time adjustments. [41,42,43]

Outcomes

Reducing reliance on imported diesel fuel:

Using renewable energy and energy storage reduces the need for imported diesel fuel. This significantly reduces reliance on external fuel sources, promoting energy security and sustainability. [41,42,43]

Costs of Energy Have Been Stabilized:

The hybrid micro-grid lowers energy costs by combining renewable energy with diesel generators. This diverse energy portfolio reduces the impact of fluctuating fuel prices and promotes predictable energy costs for the community. [41,42,43]

Increased Grid Resilience in Extreme Weather:

Using multiple energy sources, such as wind, hydropower, and diesel generators, improves grid resilience. The microgrid is built to withstand the harsh weather conditions in Alaska, ensuring continuous power supply even during storms. [41,42,43]

Conclusion

To summarize, the Kodiak Island Micro-Grid is a technically sophisticated hybrid energy system that combines renewable sources, traditional power generation, and energy storage to meet the community's specific energy needs. This technical framework ensures a reliable, cost-effective, and resilient energy supply in challenging environmental conditions.

2.3.4) Lessons Learned

Challenges

Technical: Many projects faced technical challenges in the beginning, such as integrating diverse energy sources, ensuring grid stability, and managing fluctuations in renewable energy production.

Financial constraints: The high upfront costs of micro-grid installations, as well as the ongoing maintenance requirements, have been significant challenges, particularly in economically disadvantaged areas.

Solutions

Community Engagement: Successful projects frequently involve active community participation, which ensures that the microgrid meets the community's specific needs and garners local support.

Adaptive technologies, Such as smart meters and energy storage systems, have been critical in optimizing microgrid performance and addressing technical challenges.

Replicability in a Range of Rural Contexts

Scalability: The lessons learned emphasize the importance of creating scalable models tailored to different community sizes and energy demands.

Considerations for the Local Context: Understanding and adapting to each rural context's unique socioeconomic, cultural, and geographic characteristics is critical to replication.

2.4) CONCLUSION

Rural electrification and microgrid systems have considerable promise for improving the socioeconomic situations of underserved people, particularly in areas such as the Democratic Republic of the Congo. Access to reliable electricity not only improves the quality of life by improving healthcare, education, and economic prospects, but it also helps to alleviate poverty and migratory pressures in metropolitan areas. Despite these advantages, a number of obstacles, including budgetary restrictions, technological barriers, community engagement, and regulatory issues, must be overcome in order for these programs to be viable. A balanced approach that includes both grid extension and off-grid technologies such as microgrids can give realistic electrification options. To guarantee that rural electrification programs are implemented successfully, future policies must stress community involvement, new financing structures, and stronger government commitment.

CHAPTER 3: MODELLING AND SIMULATION

3.1) INTRODUCTION

The most effective methods for integrating renewable energy in the Lubumbashi region of the Democratic Republic of the Congo were evaluated using the HOMER Pro application. The simulation, divided into three stages: defining input data, simulating each scenario, and assessing results, was used to determine system emissions, necessary capital, payback length, net present cost (NPC), and current value for each scenario.

3.2) HOMER PRO SOFTWARE

HOMER (Hybrid Optimisation Model Electric Renewable software) simulates the functioning of a hybrid microgrid over an entire year. Researchers have increasingly used HOMER to model various types of microgrids in recent years. HOMER analyses every conceivable combination of system types in a single run, sorting the systems based on the selected optimization variable.

In this work, the HOMER Pro was used to simulate and optimize the design of hybrid renewable energy systems. The application helps engineers, researchers, and energy specialists assess various hybrid power systems' technical and financial viability and determine the best configurations for a particular set of constraints. Multiple renewable energy sources (including solar, wind, and hydro), as well as traditional generators, battery power, and other energy storage devices, may all be represented in a single HOMER Pro simulation. Modelling is also possible for systems with load control and other energy-saving features. A few of the analyses that may be carried out with this program include system sizing, cost and financial and sensitivity analysis, and system optimization.

3.3) SITE DESCRIPTION

The Bandundu Province's major city is Kikwit, located southwest of the Democratic Republic of the Congo along the Kwilu River. Kikwit is also referred to as "The Mother" in the area. Five hundred sixty-eight thousand people call it home as of 2023. Kikwit is a river port and a town in the southwest of the Democratic Republic of the Congo. It is situated alongside the Kasai River's tributary, the Kwilu River. In 1901, European settlers moved to the area, and by 1910, the town had become the colonial administrative hub. The largest community in the area right now is Kikwit.
Only 4% of the 174,000 houses in Kikwit have access to electricity.

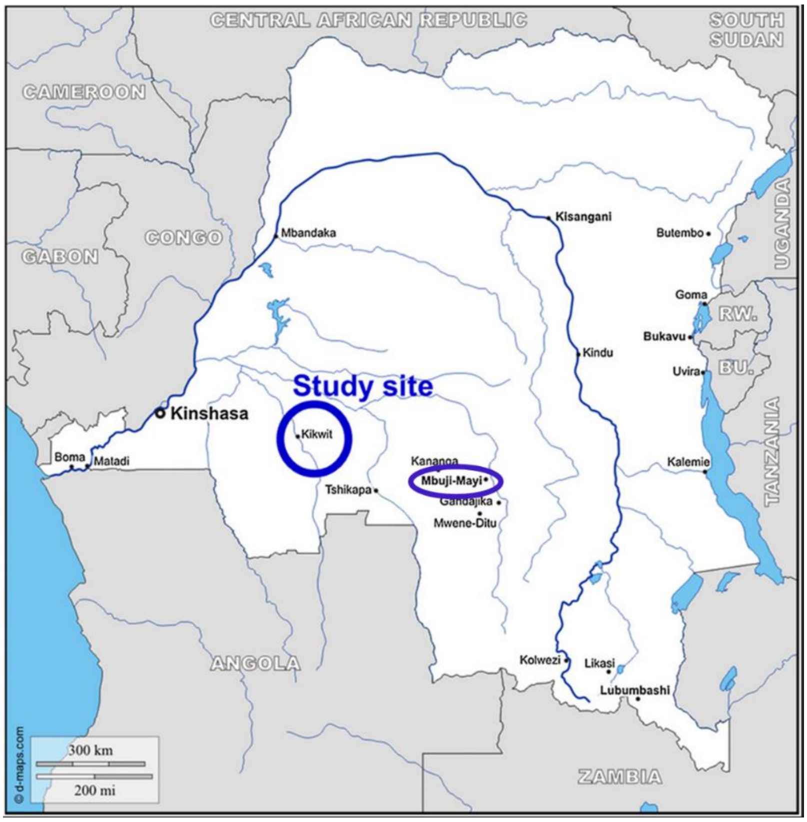


Figure 1:Map Indicating Study Site

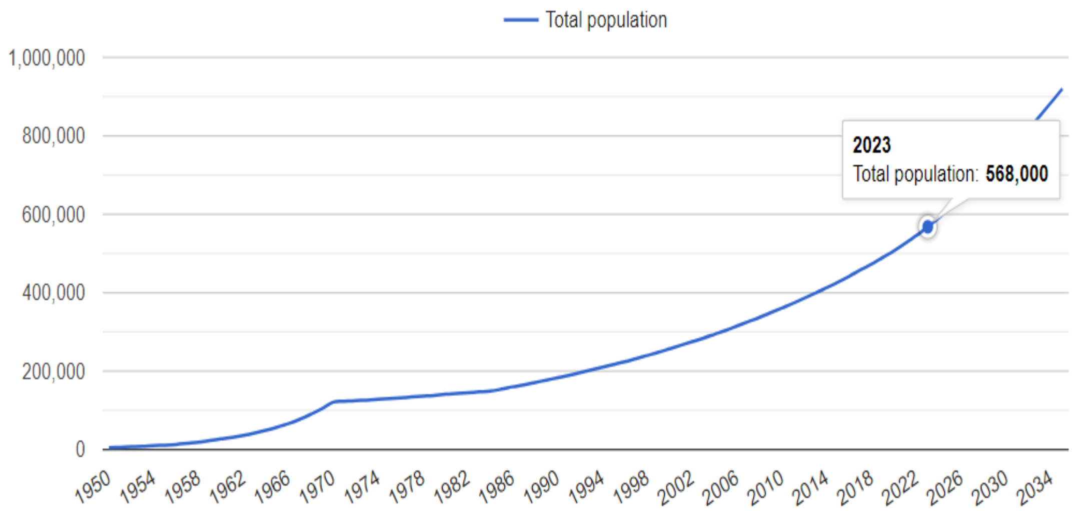


Figure 2: Kikwit Total Population

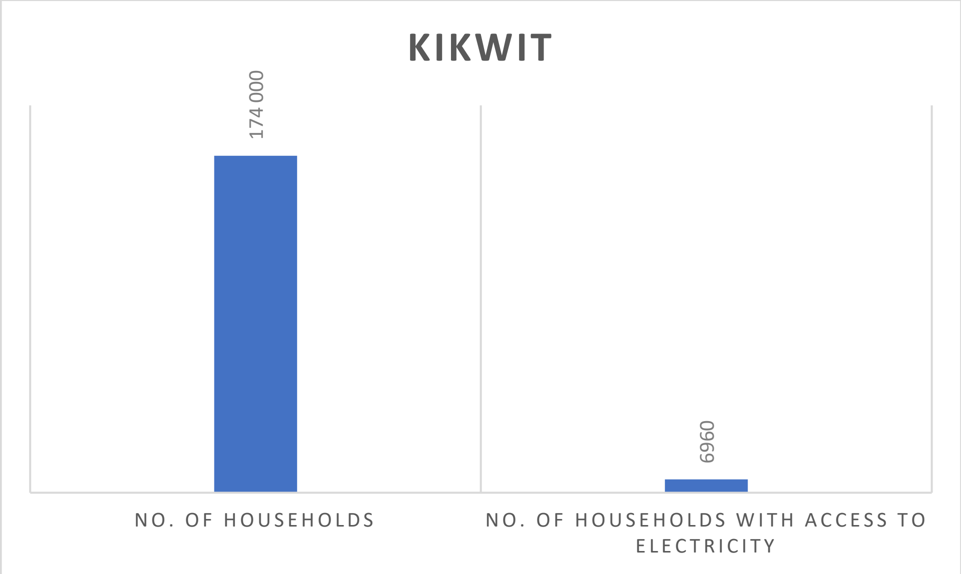


Figure 3: Number of Households vs Number of Households without Electricity

3.4) HOUSEHOLD LOAD DATA

The study aims to investigate a microgrid to power a large village in Kikwit. Typical village sizes in DRC are as follows:

A small Village is considered to consist of 10 to 25 houses.
A large village is considered to consist of 150 – 200 homes.

According to data obtained, the average household size in DRC as of 2022 is 5.3 people; for the study, the household size was chosen to be five people per household.

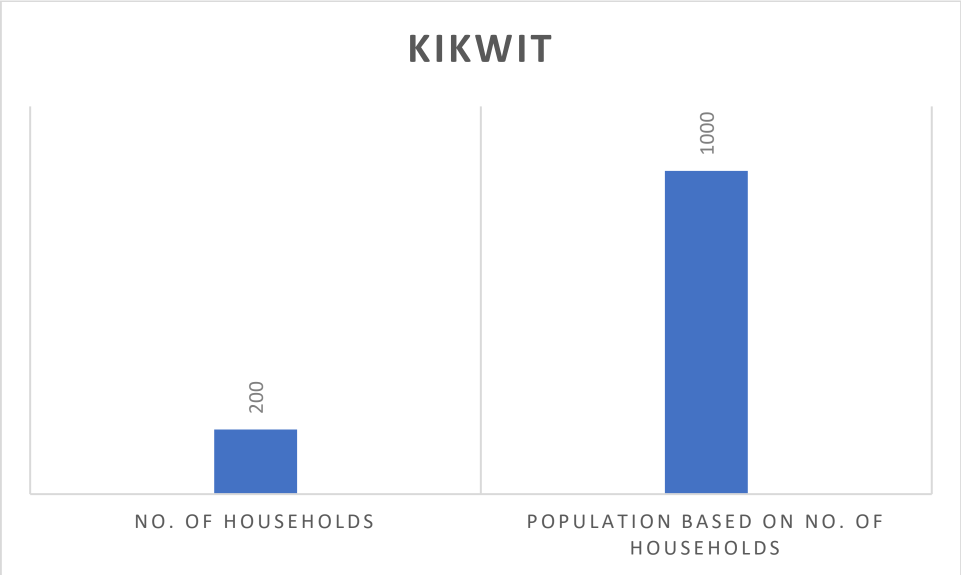


Figure 4: Total Household Population

This graph shows the average annual energy consumption per person in the DRC.

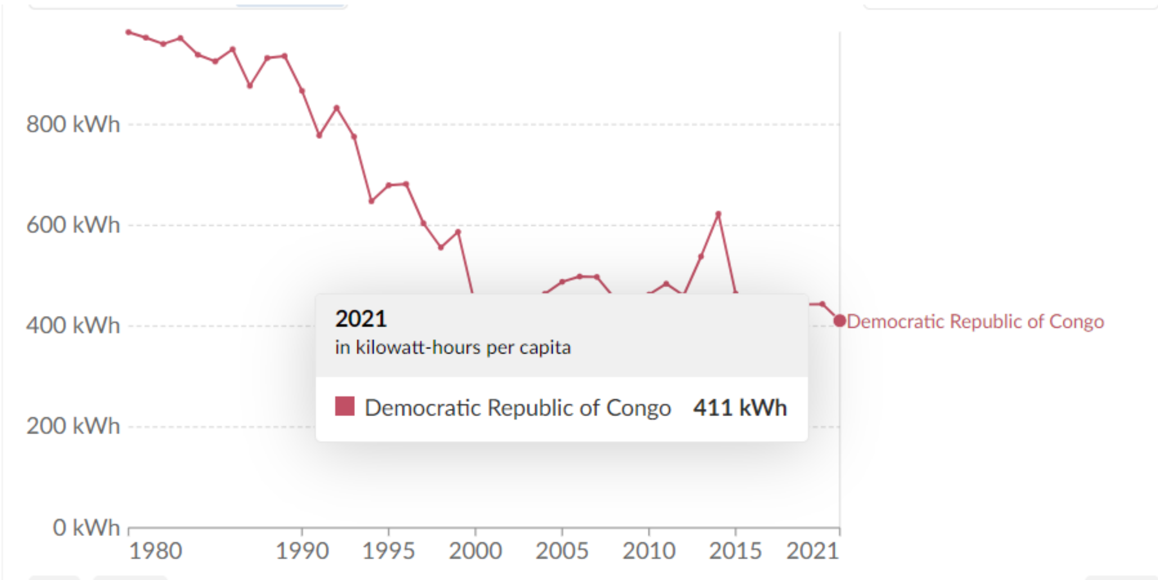


Figure 5: Average Energy Consumption per capita (IRENA)

As of 2021, the average energy consumption per person for the year amounted to 411 kWh. Based on this total, the daily loading of a large village comprising 200 households, each household comprising five people, has been calculated to be 1141.67 kWh.

Table 2: Average Electricity Consumption

Avg Consumption Per Person (yearly)	**Avg, Consumption Per Person (daily)**	**Total Avg, Consumption (200 households)**
411 kWh	1.14 kWh	1141.67 kWh

3.5) SOLAR PV PANEL

3.5.1) Solar Radiation

Figure 11 represents the monthly solar irradiance of Kikwit obtained from the NASA SEE database. The annual average of solar radiation based on the data obtained for 2022 amounts to 4.66 kWh/m^2/day. The data shows that the area has a monthly averaged daily radiation above the annual average for almost all months.

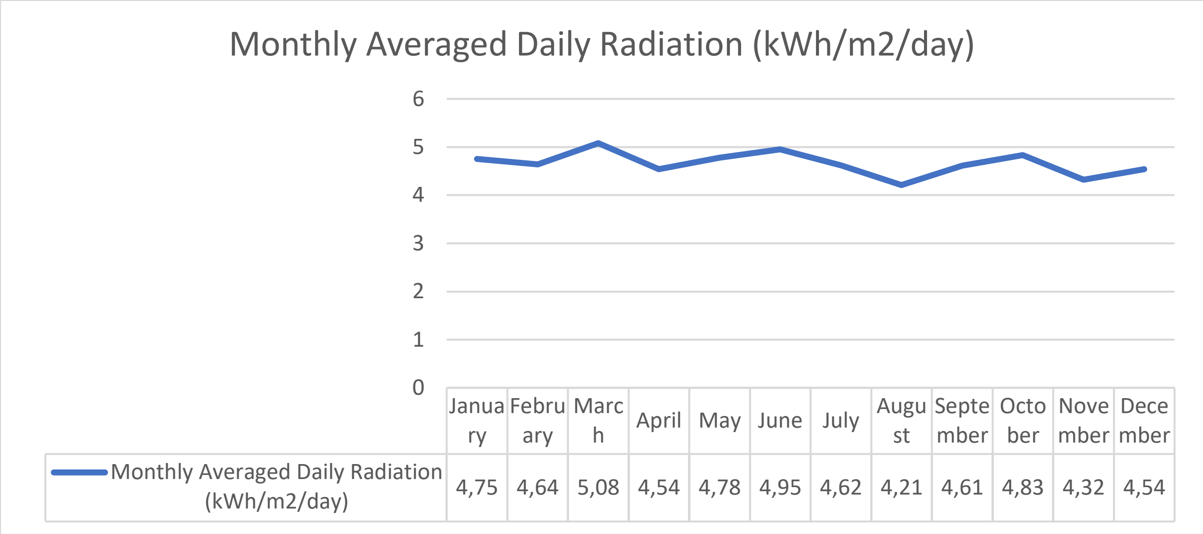


Figure 6: Monthly Average Daily radiation

The output of the PV array is calculated as follows in HOMER:

$$P_{PV} = Y_{PV}.f_{PV}\left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)\left[1+\propto_p\ (T_c - T_{c,STC})\right]$$

Where:

Y_{PV} = The PV array rated capacity. Output power at standard test conditions (kW)

f_{PV} = PV derating factor (%)

$\bar{G}_T$ = PV array solar radiation incident (kW/m^2)

$\bar{G}_{T,STC}$ = Incident radiation under standard test conditions (1 kW/m^2)

$\propto_p$ = Temperature coefficient of power (%/^{0}C)

T_c = Cell temperature of PV in current time step (^{0}C)

$T_{c,STC}$ = Cell temperature of PV under standard test conditions (25 ^{0}C)

3.5.2) Solar Cost

According to the report of IRENA, as of 2020, the average cost of a solar PV module is 0.2$/W. In DRC, the market price of solar panels varies from $800 to $2400 per kWp. This study chose the capital cost of $1500/Wp, and the optimizer setting was activated in HOMER to determine the optimal size and quantity of the PV array. Since there are no moving components and free input fuel (sunlight), the yearly operating and maintenance (O&M) and recurrent expenditures are nonexistent. The system needs simple preventative and corrective maintenance and module cleaning to operate at peak efficiency. However, maintenance costs are more significant because batteries must be replaced every three to five years in off-grid systems that employ them. It is strongly advised to use data loggers for routine monitoring to guarantee high generation and minimal maintenance costs. Maintenance expenses often amount to 2% of the system's initial cost for smaller solar PV systems, whereas for more significant systems, they typically amount to 1%. The system in this study was considered a small PV system; therefore, O&M costs were considered 2% of the initial cost, amounting to $30/year.

3.6) INVERTER AND BATTERY STORAGE

The average installed cost of utility-scale solar PV dropped from USD 1,321 per kW in 2019 to about USD 1,148 per kW in 2020, according to statistics from the International Renewable Agency (IRENA). This represents a significant 15% decrease in installation costs. Replacement cost was assumed to be the same as the capital cost, and the O&M cost was $30/year.

The nominal capacity of the battery storage chosen for the study was a 100 kWh battery. Therefore, the battery chosen can provide 100 kW of power for an hour. Coupled with the 50 kW inverter, the battery storage should provide power for at least two hours. According to figure 12, the battery capital cost of a 2-hour system, as of 2020, amounted to nearly $600/kWh or $1200/kW. As seen from the graph below, these costs will decrease over time. The expenses related to the year 2020 have been considered for the study, and therefore, the capital cost of the battery storage amounts to $60000. The replacement cost was assumed to equal the initial capital, and O&M costs $30/year.

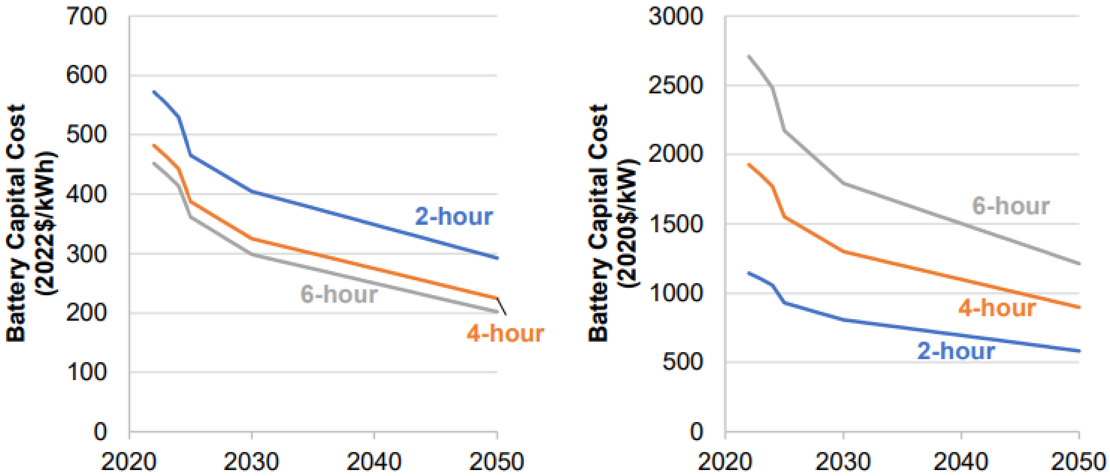


Figure 7: Battery Capital Cost

3.7) DIESEL GENERATOR

The “Autosize Genset” component has been selected in HOMER, which means the software automatically sizes the generator to meet the load and adjusts its fuel curve. The current diesel price per litre is $1.182/L. The capital cost of the generator has been considered as $500/kW, and the replacement cost is assumed to be equal to the capital cost. O&M costs were calculated in HOMER to be $0.030/hr.

3.8) NET PRESENT COST AND DISCOUNT RATE

The present value of all the expenses incurred by a component throughout its installation and operation, less the present value of all the money it generates during that period, is its net current cost, also known as life-cycle cost. The net present value of the system as a whole and each component is determined using HOMER. HOMER creates a Cash Flow table to carry out this computation.

The present value of a cash flow in any year of the project lifecycle is determined using a ratio called the discount factor. HOMER uses the following formula to determine the discount factor:

$$i = \frac{i' - f}{1 + f}$$

Where,

i	=	Real Discount Rate
i’	=	Nominal discount rate (the rate at which money is borrowed)
f	=	Expected inflation rate

As of September 2023, The Democratic Republic of the Congo's central bank increased the benchmark interest rate to 25%. The inflation rate currently stands at 10.76%. Based on these values, the Real Discount Rate can be calculated as follows, using equation 2:

$$i = \frac{i' - f}{1 + f}$$

$$i = \frac{25\% - 10.76\%}{1 + 10.76\%}$$

$$i = 12.87\%$$

3.9) DISCOUNT FACTOR

The present value of a cash flow in any year of the project lifecycle is determined using a ratio called the discount factor. HOMER uses the following formula to determine the discount factor:

$$f_d = \frac{1}{(1+i)^N}$$

Where.

i	=	Real discount rate
N	=	Number of years

CHAPTER 4: RESULTS, DISCUSSION AND CONCLUSION

This chapter delves into the substantive findings from the comparative evaluation of two prominent energy systems: a standalone diesel generator and a hybrid microgrid incorporating solar photovoltaic (PV) technology, battery storage, and a diesel generator.

Schematic

Figure 8 is a visual depiction of the system schematic, providing a thorough overview of the hybrid microgrid configuration being studied in the context of rural electrification in Kikwit.

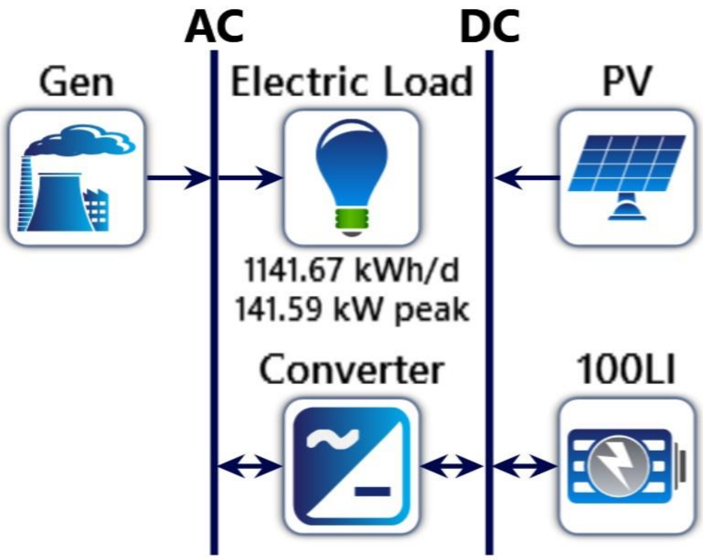


Figure 8: System Schematic

4.1) BASE CASE

Table 3: Base Case System Architecture

COMPONENT	NAME	SIZE	UNIT
Generator	Autosize Genset	160	kW

Table 4: Base Case Cost Summary

Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total NPC ($)
$80,000.00	$886,430.61	$830,149.91	$3,600,331.02	-$19,964.60	$5,376,946.95

The base case scenario consisted of a 160 kW diesel generator to accommodate the load of 141.59 kW peak.

The entire installed cost of a component at the start of the project is its initial capital cost. Since the initial capital cost of the generator has been selected as $500/kW, the total capital cost of the 160 kW generator amounts to $80 000 ($500 x 160 kW). The total Net Present Cost (NPC) of the generator system, factoring in capital costs, replacement costs, O&M and fuel expenses, and salvage, amounts to $5 376 946.95, as seen in Table 7.

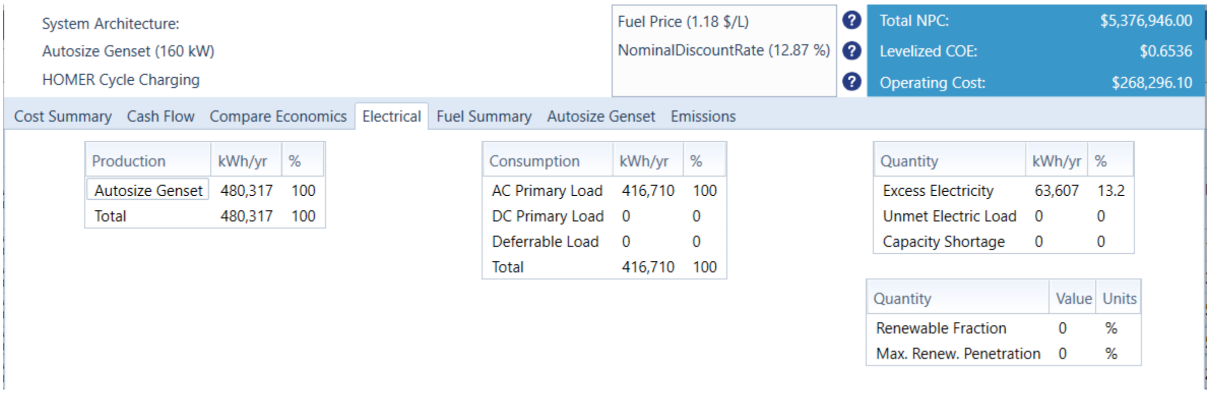


Figure 9: Base Case Electrical Analysis

Figure 9 represents the electrical analysis results of the base case diesel generator. The main results in Figure 9, which are the production, consumption and excess electricity, are graphically presented in Figure 10.

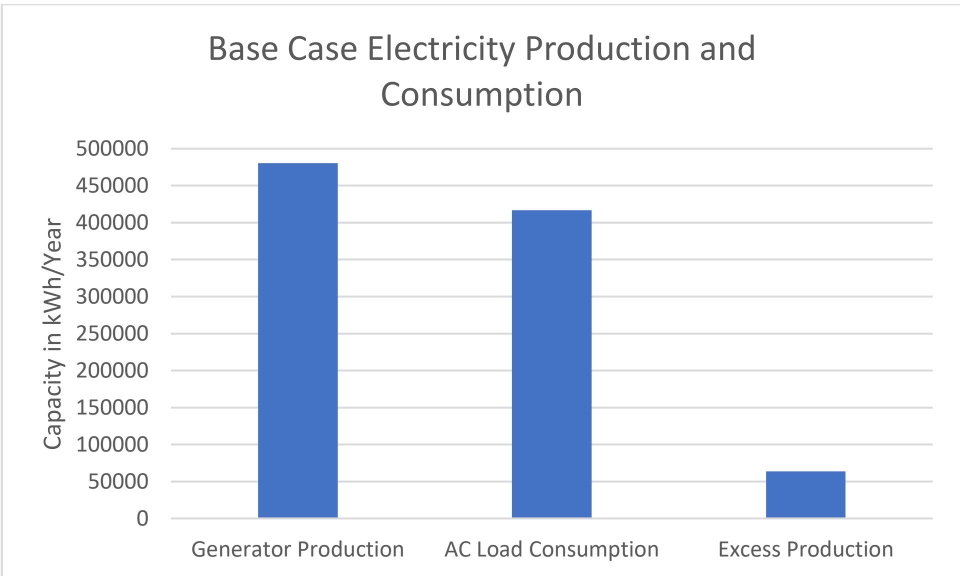


Figure 10: Base Case Electricity Production and Consumption

According to the statistics generated by HOMER, more power is available since the generator's annual energy production surpasses the annual AC load consumption. This extra energy generation can accommodate future load increases. Let's examine the relevance and ramifications of this discovery:

- Annual Power Production of the Generator (480,317 kWh/yr): This amount shows how much power the diesel generator in Kikwit produces in a whole year. Remembering that the generator's efficiency and capacity determine this production is crucial.

- Total Annual AC Consumption (416,710 kWh/yr): This figure shows how much power each of the 200 Kikwit homes used overall in a given year. It covers the community's electrical appliances, lights, and other power requirements.

- Future Load Growth Accommodation: Extra power is a valuable resource for future increases in electricity demand. As towns grow, more homes, businesses, and infrastructure may need more power. Kikwit has the buffer to handle these rising needs without having to expand the energy infrastructure immediately, thanks to its 63,607 kWh/yr excess.

- Sustainability and Reliability: This excess electricity may make Kikwit's energy supply more reliable and sustainable. It offers a safety cushion to guarantee that the community's energy requirements can be satisfied even during high demand or unanticipated events.

Quantity	Value	Units
Hours of Operation	8,760	hrs/yr
Number of Starts	1.00	starts/yr
Operational Life	1.71	yr
Capacity Factor	34.3	%
Fixed Generation Cost	15.7	$/hr
Marginal Generation Cost	0.279	$/kWh

Quantity	Value	Units
Electrical Production	480,317	kWh/yr
Mean Electrical Output	54.8	kW
Minimum Electrical Output	40.0	kW
Maximum Electrical Output	142	kW

Quantity	Value	Units
Fuel Consumption	154,281	L
Specific Fuel Consumption	0.321	L/kWh
Fuel Energy Input	1,518,129	kWh/yr
Mean Electrical Efficiency	31.6	%

Figure 11: Base Case Diesel Generator Quantities

Fuel costs are essential when assessing a diesel generator's operating efficiency and financial feasibility. Factors such as the generator's loads and operating hours affect the fuel cost. A diesel generator's fuel expenditure correlates directly with the hours it runs. In other words, the longer the generator works, the more fuel it uses, which drives fuel prices. It's important to remember that fuel is consumed by the generator even when it is not producing any electricity. Reducing fuel expenses requires minimizing idle time and ensuring the generator runs only when needed. Optimizing fuel efficiency through regular maintenance and repair may decrease long-term fuel consumption. Fuel efficiency-related problems can be found and fixed with routine maintenance.
A diesel generator's loading has a direct impact on its fuel costs. Fuel efficiency is often higher when operating a generator at a more significant proportion of its rated load. Diesel generators exhibit superior fuel economy, often using 75–80% of their rated load.

From the results obtained from HOMER, it can be seen that the operational hours of the generator a year amount to 8 760 hours/yr and a total fuel consumption of 154 281 litres.

The average fuel the generator uses per kWh of power produced is the specific fuel consumption. HOMER uses the following formula to get the precise fuel consumption:

$$F_{spec} = \frac{F_{tot}}{E_{gen}}$$

Where,

F_{tot} = Annual total consumption of generator fuel (L/yr).

E_{gen} = Annual total electricity production of the generator (kWh/yr).

Therefore, from the results obtained from HOMER, using equation ___:

$$F_{spec} = \frac{154281}{480317}$$

$$F_{spec} = 0.321\ L/kWh$$

In conclusion, operating hours and loading significantly impact a diesel generator's fuel cost. Fuel expenses may be managed by maximizing operating hours by cutting idle time and performing routine maintenance. The generator must also be operated at a loading level closer to its rated load for fuel economy.

Figure 12 represents the emissions results obtained from HOMER for the base case. These quantities have been added to a pie chart in Figure 13 and further discussed.

Quantity	Value	Units
Carbon Dioxide	403,849	kg/yr
Carbon Monoxide	2,546	kg/yr
Unburned Hydrocarbons	111	kg/yr
Particulate Matter	15.4	kg/yr
Sulfur Dioxide	989	kg/yr
Nitrogen Oxides	2,391	kg/yr

Figure 12: Base Case Emissions Homer Results

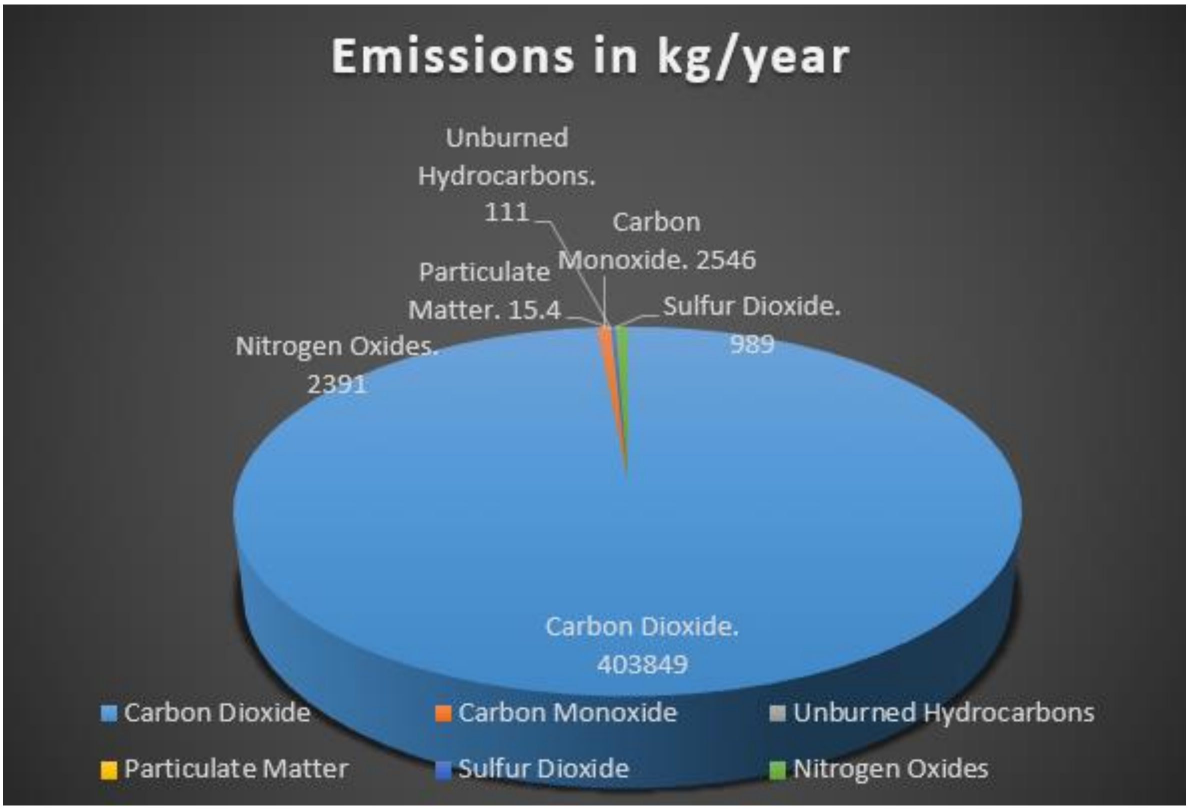


Figure 13: Base Case Emissions

The emissions results obtained from the HOMER simulation show that carbon dioxide is the bulk of the emissions formed when operating the diesel generator and unburned hydrocarbons and particulate matter the least.

A colourless and odourless gas known as carbon dioxide (CO_2) is created when diesel fuel burns. It's a significant greenhouse gas. Because of the fuel's carbon content, diesel generators emit CO_2 emissions, closely correlated with fuel consumption. One of the leading causes of climate change and global warming is O_2. Heat is trapped as CO_2 builds up in the atmosphere, increasing world temperatures and climate-related effects. Improving fuel economy and switching, where practical, to greener energy sources, such as natural gas or renewable energy, are two ways to reduce CO_2 emissions from diesel generators. Programs for carbon offsets are a further option.

Organic substances made up of hydrogen and carbon atoms are known as hydrocarbons. They refer to fuel components that have been partially or entirely burnt and are discharged into the atmosphere when discussing emissions from power generation. The primary source of hydrocarbon emissions is incomplete fossil fuel combustion, mostly in gas turbines and internal combustion engines. Hydrocarbon emissions come from diesel generators and some natural gas power plants. One of the leading causes of smog is ground-level ozone, which is formed by hydrocarbon emissions. In addition to harming flora, ground-level ozone can negatively affect respiratory health. Maintaining engine or turbine efficiency, improving fuel quality, and streamlining combustion processes are all crucial for lowering hydrocarbon emissions.

Tiny solid or liquid particles floating in the air are called particulate matter. It mainly comprises fine particles created when diesel fuel is burned in diesel generators. Diesel fuel contains impurities, which lead to incomplete combustion and particulate matter emissions. Cardiovascular and respiratory issues are among the significant health impacts of delicate particulate matter (PM2.5). PM10, or coarser particles, can affect the environment and human health.

Nitric oxide (NO) and nitrogen dioxide (NO2) are examples of nitrogen oxides, sometimes known as NOx. These are created when diesel fuel burns at a high temperature. The combustion process in diesel generators produces NOx emissions, and greater temperatures promote the creation of NOx. NOx has a role in the creation of smog and ground-level ozone. It can cause respiratory irritation, worsen existing respiratory disorders, and have negative environmental impacts such as acid rain and vegetation destruction.

Burning diesel fuel containing sulfur releases sulfur dioxide (SO2), a colourless gas with a pungent stench. Diesel fuel's sulfur concentration is what causes SO2 emissions. Fuels with less sulfur release less SO2. Acid rain can be created when SO2 reacts with other substances in the atmosphere. It irritates human respiratory tracts and can damage buildings, forests, and aquatic environments.

In conclusion, the aim is to keep all these emissions to the absolute minimum to prevent and lessen the impact of these gasses on the environment.

4.2) BEST CASE SCENARIO

Table 5 represents the system components and each component size of the best-case scenario generated from HOMER. From the information presented in Table 5, it can be noted that the generator and its size have remained the same. The additions to the system are PV panels, a converter and battery storage.

Table 5: Best Case System Architecture

COMPONENT	NAME	SIZE	UNIT
Generator	Autosize Genset	160	kW
PV	Generic Flat plate PV	370	kW
Storage	Generic 100 kWh Li-ion	10	Strings
System Converter	System Converter	117	KW

Figure 14 represents the cost summary results obtained from HOMER. These results have been tabulated in Table 6 and compared with the base case results.

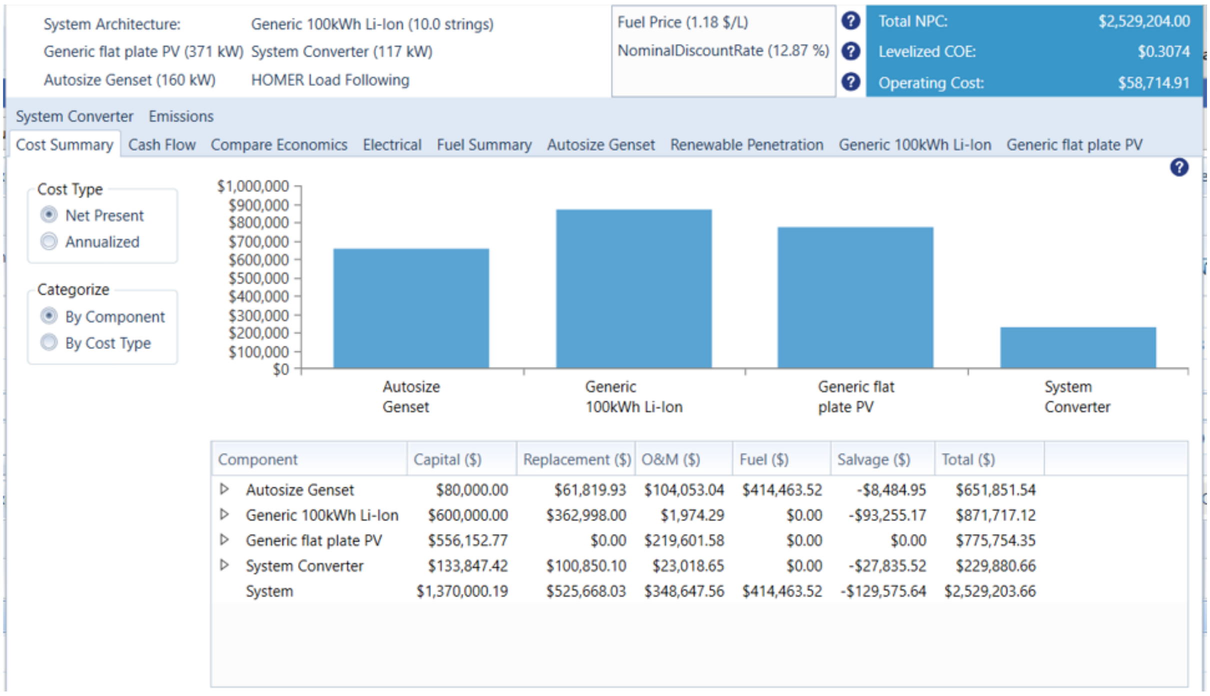


Figure 14: Best case Cost Summary

Referring to Table 6, the best-case scenario, a hybrid system with several energy sources, is contrasted with the primary system, a stand-alone diesel generator, to highlight the need to consider other energy options. The best-case scenario in this situation is more advantageous economically. With the best-case system, there is a significant cost savings of $2,847,743.29 because of the difference in NPC. This shows that throughout the project, the hybrid system—which combines solar PV with battery storage—is more economical.

Table 6: Base Case Cost vs Best Case Cost

BASE CASE							BEST CASE						
COMPONENT	CAPITAL	REPLACEMENT	O&M	FUEL	SALVAGE	TOTAL NPC	COMPONENT	CAPITAL	REPLACEMENT	O&M	FUEL	SALVAGE	TOTAL NPC
Generator	$80,000.00	$886,430.61	$830,149.91	$3,600,331.02	-$19,964.60	$5,376,946.95	Generator	$80,000.00	$61,819.93	$104,053.04	$414,463.52	-$8,484.95	$651,851.54
							Storage	$600,000	$362,998.00	$1,974.29	0	-$93,255.17	$871,717.12
							PV	$556,152.77	$0	$219,601.5	0	0	$775,754.35
							Converter	$133,847.42	$100,850.10	$23,018.65	0	-$27,835.52	$229,88.66
System Total	**$80,000.00**	**$886,430.61**	**$830,149.91**	**$3,600,331.02**	**-$19,964.60**	**$5,376,946.95**	**System Total**	**$1,370,000.19**	**$525,668.03**	**$348,647.56**	**$414,463.52**	**-$129,575.64**	**$2,529,203.66**

Fuel prices are the leading cause of the higher NPC in the base system. This is an important discovery because it emphasizes the financial benefit of lowering reliance on diesel fuel, which can be expensive and volatile.

The significant variation in NPC between the primary and best-case systems highlights the significance of investigating more all-encompassing and environmentally friendly energy options. In addition to producing considerable cost savings, switching from a standalone diesel generator to a hybrid system with renewable energy sources and storage is also in line with long-term viability, economic, and environmental concerns. This research emphasizes how important it is to fund greener and more sustainable energy sources for the good of the environment and the community.

Quantity	Value	Units
Hours of Operation	1,098	hrs/yr
Number of Starts	461	starts/yr
Operational Life	13.7	yr
Capacity Factor	3.82	%
Fixed Generation Cost	15.7	$/hr
Marginal Generation Cost	0.279	$/kWh

Quantity	Value	Units
Electrical Production	53,519	kWh/yr
Mean Electrical Output	48.7	kW
Minimum Electrical Output	40.0	kW
Maximum Electrical Output	132	kW

Quantity	Value	Units
Fuel Consumption	17,761	L
Specific Fuel Consumption	0.332	L/kWh
Fuel Energy Input	174,764	kWh/yr
Mean Electrical Efficiency	30.6	%

Figure 15: Best Case Diesel Generator Quantities

Table 7: Diesel Generator Quantities - Base Case vs Best Case

BASE CASE						BEST CASE					
OPERATIONAL HOURS	NO. OF STARTS	OPERATIONAL LIFE	ELECTRICAL PRODUCTION	FUEL CONSUMPTION	SPECIFIC FUEL CONSUMPTION	OPERATIONAL HOURS	NO. OF STARTS	OPERATIONAL LIFE	ELECTRICAL PRODUCTION	FUEL CONSUMPTION	SPECIFIC FUEL CONSUMPTION
8760 hrs/yr	1 start/yr	1.71 yr	480 317 kWh/yr	154 281 Litres	0.321 L/kWh	1098 hrs/yr	461 starts/yr	13.7 yr	53 519 kWh/yr	17 761 Litres	0.332 L/kWh

A noteworthy change in the energy system is highlighted by the observation made from the findings in Figure 15, which shows a reduction in the generator's operating hours to 1,098 hours annually and corresponding total fuel consumption of 17,761 litres. The fuel costs have significantly decreased as a result of this adjustment in comparison to the base scenario (tabulated in Table 7). The data also suggests some important conclusions:

- Operational Efficiency: The generator appears to be operating annually for a reduced amount of time based on the decline in working hours. This is explained by the hybrid system's extra energy sources, especially solar PV and battery storage, which may balance out electricity demand without always using the generator.

- Fuel usage Reduction: There has been a noticeable drop in fuel usage due to the shorter operating hours. Reducing the number of hours the generator runs also means using less fuel, which significantly adds to the total energy expenses of systems that use diesel generators.

- Cost Savings: There are considerable cost savings due to the reduced gasoline usage. Particularly with diesel generators, the cost of fuel can account for a sizable portion of overall operating costs. One of this system's economic benefits is that it uses less gasoline under the best-case situation.

- Environmental Impact: Lowering fuel use also results in lower emissions of greenhouse gases and other pollutants brought on by burning fossil fuels. This more responsible and environmentally friendly energy option aligns with sustainability and environmental aims.

- Energy Resilience: Even if the generator runs for shorter periods, it plays a significant part in preserving energy resilience. The generator can be a backup in times of high demand, blackouts, or when renewable energy sources like solar power are unavailable, ensuring that the community's electrical demands are constantly supplied.

- Energy Supply Balancing: Better control of energy supply and demand is probably made possible by the existence of solar PV and battery storage. Reliance on the generator during off-peak hours can be decreased by storing excess power produced during sunny periods in the batteries and using them when needed.

Table 7 offers essential insights into how combining renewable energy sources and battery storage may maximize the diesel generator's operation and durability by comparing the generators' amounts in the base case and the best-case scenario. This finding has several significant ramifications:

- Extended Operational Life: The diesel generator's operational life is extended to 13.7 years with fewer operating hours per year. This longer lifespan is a good thing since it implies that the generator won't need to be changed as often, which will save money during the project's lifetime.

- Increased Starts: In the best-case situation, the diesel generator needs 461 starts annually. The generator's repeated starting and stopping corresponds with its more deliberate use, which lengthens its lifespan.

- Decrease in Replacement Costs: Over the project, the generator's replacement costs will be lower due to a longer operating life and fewer replacements. This is a significant cost-saving measure because replacing a diesel generator might involve a substantial financial outlay.

- Dependability and Resilience: In the best-case scenario, the diesel generator still plays a crucial part in guaranteeing the dependability and resilience of the energy supply, even with the rise in starts. It is a backup in times of high demand or the absence of renewable energy sources.

To summarise, Table 7 presents the benefits of incorporating energy storage and renewable energy sources into the energy system. Throughout the project, this strategy reduces fuel consumption, extends the operational life of the diesel generator, and saves money by optimizing its operation and lifespan. Additionally, it strengthens the energy supply's dependability and resilience, making it a comprehensive and long-lasting solution for the community.

Figure 16 offers essential insights into seasonal fluctuations in energy output and the feasibility of solar PV as an energy source in Kikwit's location. It compares the monthly power production from solar PV to the generator.

Considerable seasonal changes in energy output are shown in the graph. Solar photovoltaics (PV) displays a notable variation in power output across months, indicative of the fluctuating strength and length of sunshine throughout the year. These fluctuations are normal for places at specific latitudes where the length and angle of sunlight vary with the seasons.

For Kikwit, solar photovoltaics (PV) becomes a practical and dependable energy source, especially in some months. The graph demonstrates how, in some months, solar photovoltaics may provide almost all of the power needed. This implies that solar PV can provide the community's power needs for a significant portion of the year. June and July are particularly notable for having very high solar PV production. The solar energy output is so intense during these months that the generator is used as little as possible. This is an important discovery since it lowers operating expenses and supports sustainability objectives by reducing the need for the generator, which frequently burns fossil fuels.

Figure 16: Best Case Electricity Production and Consumption

In conclusion, Figure 16 shows how highly viable solar photovoltaic (PV) energy may be in Kikwit, especially in summer. The information emphasizes how crucial it is to match energy sources to regional climates and use renewable energy at peak output times. This lowers operating expenses and makes the energy system more ecologically friendly and sustainable.

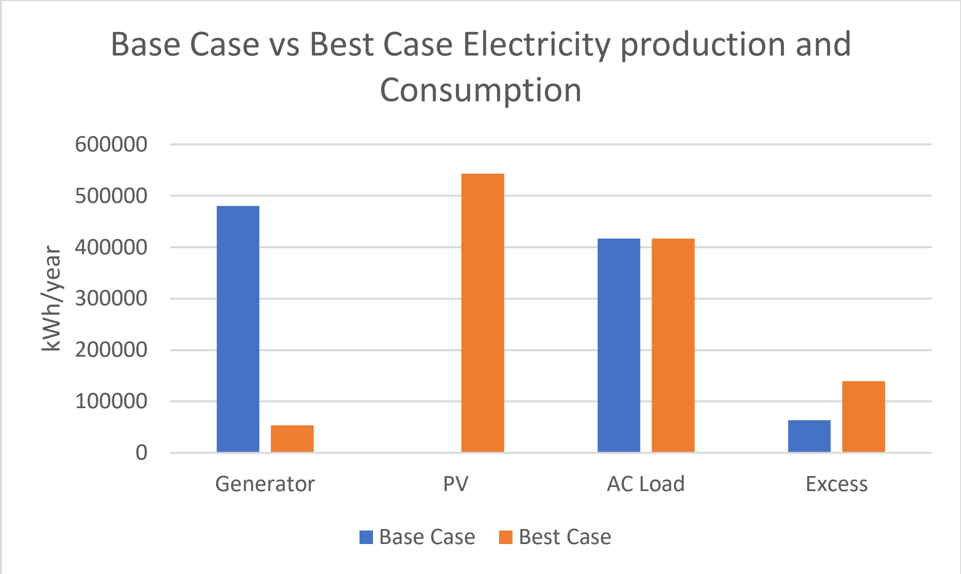


Figure 17: Electricity Production and Consumption - Base Case vs Best Case

A comparison of the power output and consumption between the Best Case (a hybrid system with solar PV) and the Base Case (a standalone diesel generator) can be found in Figure 17. The findings shed light on the significant impact of incorporating solar photovoltaics into the energy grid. The following is the technical analysis:

- Diminished Generator Electricity Production: One of Figure 15's most notable discoveries is the Best Case's significant decrease in generator electricity production compared to the Base Case. The existence of solar PV, which can supply a sizable amount of the power demand during daylight hours, is credited with this decrease. This result illustrates how the energy system becomes more cost-effective and efficient when renewable energy sources are included.

- Increased Excess Electricity: The Best Case shows a significant rise in excess electricity, another important finding. The extra energy produced above what is used is known as excess electricity, and it is an essential indicator of the resilience of the energy system and its ability to support future expansion. In the best-case scenario, the excess has increased from 63,607 kWh/year to 139,238 kWh/year. This notable rise in extra power shows that the hybrid system can prepare for future load increases and meet present demands.

- Optimal Resource Usage: The Best Case illustrates how resources are used optimally. Solar PV enhances the generator's performance by producing power while the sun shines. The generator's total operating hours are decreased by carefully filling up power shortages caused by insufficient solar output. This selected operation reduces fuel consumption and operating expenses.

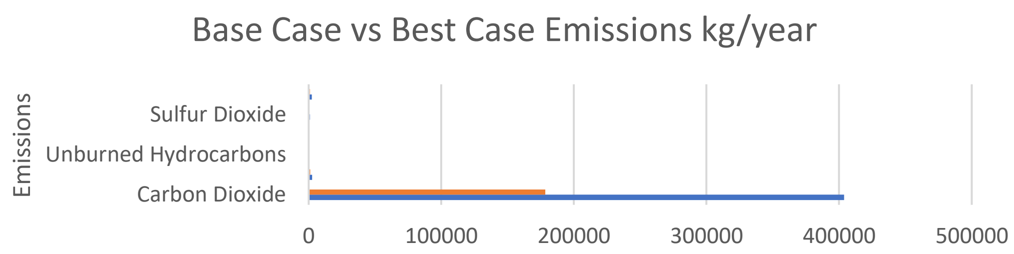
- Benefits to the Environment and Economy: The information in Figure 15 highlights the benefits of the Case scenario to the environment and economy. Cost reductions and a smaller carbon impact result from the decrease in generator use and the rise in surplus power. It is possible to store the extra power for use during times of greater demand or to use it as leverage for economic growth.

- Energy Security and Future-Proofing: The increased electrical surplus improves the community's energy security. In addition to guaranteeing a steady power supply, it fortifies the system against rising electricity use in the future, promoting the expansion and advancement of the local community.

Quantity	Value	Units
Carbon Dioxide	46,490	kg/yr
Carbon Monoxide	293	kg/yr
Unburned Hydrocarbons	12.8	kg/yr
Particulate Matter	1.78	kg/yr
Sulfur Dioxide	114	kg/yr
Nitrogen Oxides	275	kg/yr

Figure 18: Best Case Emissions

Significant information on the environmental effect of the energy system can be found by comparing Figure 18 (emissions statistics for the Best Case scenario) and Figure 19 (a graphical representation comparing the Best Case to Base Case). This talk focuses on lowering carbon dioxide (CO2) emissions and the environmental advantages of switching from the Base Case (a standalone diesel generator) to the Best Case (a hybrid system with solar PV and battery storage).



	Carbon Dioxide	Carbon Monoxide	Unburned Hydrocarbons	Particulate Matter	Sulfur Dioxide	Nitrogen Oxides
Best Case	178556	1126	49,1	6,82	437	1057
Base Case	403849	2546	111	15,4	989	2391

Figure 19: Emissions - Base Case vs Best Case

Carbon dioxide (CO2) is the main greenhouse gas responsible for most of the emissions generated by the diesel generator in the Base Case, as Figure 19 makes abundantly evident. Because CO2 emissions have a proven link to climate change and global warming, they are a severe problem. The significant amount of CO2 emissions highlights how critical it is to solve this problem.

Reducing the energy system's adverse effects on the environment and the world, especially CO2 emissions, is the aim of the Best-case scenario. The diesel generator may run more selectively and efficiently thanks to solar PV and battery storage installation. It doesn't run constantly throughout the project's duration; instead, it only operates as required, as a backup or when solar production is insufficient. In the best-case scenario, the diesel generator's shortened operating hours drastically cut CO2 emissions. The Best Case prevents continuous running and uses less fuel, which reduces the amount of CO2 released into the atmosphere. This aligns with sustainability and environmental responsibility objectives since it helps mitigate climate change by lowering the greenhouse impact.

Environmental sustainability has significantly improved due to the Base Case to Best Case shift. In addition to lowering operating expenses, the Best Case offers the community a more sustainable and ecologically friendly energy option by utilizing energy storage and renewable energy sources. This change is essential to reducing the harmful environmental impacts of running diesel generators the old-fashioned way.

In conclusion, comparing emissions data between the Base Case and Best Case scenarios emphasizes the advantages of switching to a hybrid system with solar PV and battery storage for the environment. The deliberate cutback in the diesel generator's running hours dramatically reduces CO2 emissions, promoting a greener and more sustainable energy system. This shift is critical to solving the world's climate concerns and being economically beneficial.

4.3) ECONOMICS COMPARISON

The economic comparison conducted in this study is a critical component of the research, offering light on the cost consequences and viability of two different energy options in the context of rural electrification in Kikwit. The economics comparison aims to disentangle the complex web of cost elements, income streams, and financial measures that support the decision-making process for energy infrastructure projects through thorough study and quantitative assessment.

	Architecture				Cost	
	PV (kW)	Gen (kW)	100LI (#)	Converter (kW)	NPC ($)	CAPEX ($)
Base system		160			$5.38M	$80,000
Proposed system	371	160	10	117	$2.53M	$1.37M

Metric	Value
Present worth ($)	$2,847,743
Annual worth ($/yr)	$144,241
Return on investment (%)	12.3
Internal rate of return (%)	16.3
Simple payback (yr)	5.76
Discounted payback (yr)	6.09

Figure 20: Economics Results - Base Case vs Best Case

Figure 20 represents the economics comparison produced by HOMER for the base case and best case (proposed system).

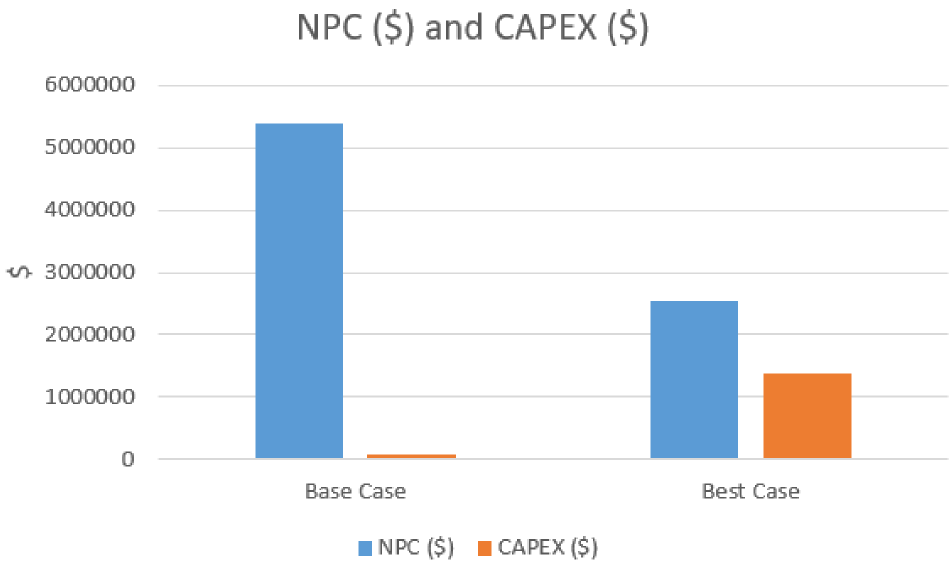


Figure 21: NPC and CAPEX - Base Case vs Best Case

Figure 21 compares the NPC and CAPEX associated with the base case system and best case system obtained in Figure 18.

The NPC cost of the base case system is \$5.38 million, and capital expenditure is \$80k. The NPC cost of the proposed system amounts to \$2.53 million, and capital expenditure amounts to \$1.37 million.

The difference between the base case system's and the current system's net present costs is known as the present worth. The sign of the present worth shows whether the current system compares favourably to the base case system as an investment choice: When compared to the base case system, a positive number means that the current system will save money throughout the project.

The present worth of the system, as shown in the HOMER results, is calculated as follows:

$$Present\ worth = NPC_{base} - NPC_{best}$$
$$Present\ worth = \$5.38\ million - \$2.53\ million$$
$$Present\ worth = \$2.85\ million$$

The present value multiplied by the capital recovery factor equals the annual worth. An annuity is a series of equal yearly cash payments, and its current value is determined using a ratio called the capital recovery factor.

The ROI number, presented as a percentage, sheds light on how financially successful the project was. It illustrates, in particular, the anticipated return or profit on the project's initial investment. A positive return on investment (ROI) denotes the expectation of a profit during the project's lifetime. A financially feasible project often has a favourable return on investment.

Concerning Figure__, it is shown that the ROI for the proposed system is a positive value of 12.3%. As discussed, this represents that the proposed system is financially feasible as it has a favourable return on investment.

While ROI is a valuable indicator, it should be compared to other financial metrics such as payback periods, Net Present Value (NPV), and Internal Rate of Return (IRR) to have a complete picture of a project's risk profile and financial sustainability. These indicators support well-informed investment choices, especially in energy projects with critical long-term economic consequences.

The lifetime cost of energy generated over a project's lifetime, expressed as a kilowatt-hour (kWh), is represented by the term "LCOE." It accounts for all pertinent expenditures, including gasoline and finance charges, original capital costs, operating costs, and continuing maintenance.

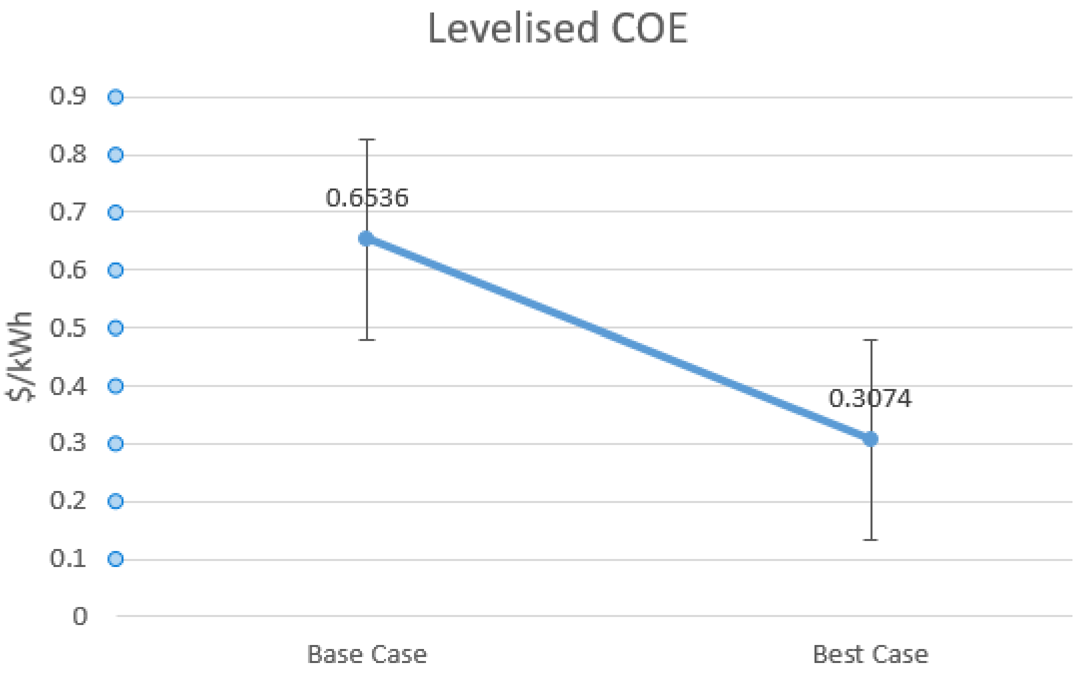


Figure 22: Levelised Cost of Energy - Base Case vs Best Case

A lower LCOE suggests a more economical way to produce power. In contrast, higher energy-generating costs are indicated by a larger LCOE. Figure 22 represents the LCOE for the base case and best-case systems. As we can see, the base case has an LCOE of 0.6536 $/kWh and, in the best case, an LCOE of 0.3074 $/kWh.

It's critical to consider the unique circumstances of the projects or technologies under evaluation when comparing LCOEs. Numerous variables affect the LCOE, such as the selected technology, fuel prices, project size, financing conditions, and location. In terms of the base case and best case, the main contributing factors to the lower LCOE of the best case, based on the results obtained, would be fuel costs and operating and maintenance costs of the diesel generator. As discussed, the diesel generator in the base case must be used for 8760 hours/year compared to the 1098 hours/year in the best case. The longer the generator is needed to operate, the greater the cost of fuel consumption, the decrease in operational life, and the more significant the O$M costs. In the base case, the diesel generator has an active life of 1.71 years before it needs to be replaced, whereas in the best case, the diesel generator has an operational life of 13.7 years before needing to be replaced.

4.4) CONCLUSION

The socioeconomic examination of energy-related solutions for rural communities—especially in the context of Kikwit—has made it evident where sustainable development and improved well-being are headed. After a thorough examination, two suggested systems—a standalone diesel generator and a hybrid microgrid with solar PV, battery storage, and a diesel generator—were shown to have different results.

The findings clearly show that the hybrid microgrid is more financially viable and significantly more advantageous for the Kikwit community. With the sustainability of solar PV and energy storage coupled with the dependability of a diesel generator, this cutting-edge system provides a complete and creative answer to rural families' energy demands.

The following essential study findings highlight the benefits of the hybrid microgrid:

Economic Viability: Compared to a standalone diesel generator, the hybrid microgrid has a much lower Levelized Cost of Electricity (LCOE). The neighbourhood will gain economically significantly from this decreased operating expenses and fuel use.

Enhanced power Supply: The hybrid microgrid performs noticeably better than the standalone diesel generator in terms of power output. In addition to satisfying the current demand, it provides the opportunity for more electrification, fostering economic expansion and better living standards.

Environmental Impact: Reducing greenhouse gas emissions is one of the hybrid microgrid's most notable contributions. This accomplishment improves the region's ecological well-being and aligns with global sustainability goals.

Energy Access and Dependability: The hybrid microgrid dramatically enhances energy access and dependability by lowering reliance on expensive and unpredictable diesel fuel. This improves the community's quality of life, impacting productivity, healthcare, and education.

In summary, the decision between the hybrid microgrid and the standalone diesel generator is not just based on cost; it also pits resilience and sustainability against vulnerability and resource depletion. The advantages of the hybrid microgrid go well beyond financial gain; they also impact more general issues like community growth, environmental stewardship, and a sustainable future for rural homes in Kikwit. The best and most innovative option is the hybrid microgrid, which consists of solar PV, battery storage, and a diesel generator. The community will benefit economically and environmentally from its implementation, which will also significantly advance universal access to renewable energy. This dissertation presents a perspective and an analysis of how rural communities might adopt sustainable energy solutions to improve their socio-economic well-being and protect the environment for coming generations.

4.5) RECOMMENDATIONS FOR FURTHER RESEARCH

While this study sheds light on the comparative benefits of a hybrid microgrid over a solo diesel generator for rural electrification in Kikwit, more research may go deeper into numerous areas to improve knowledge and optimize energy solutions in comparable situations. Here are some suggestions for further research:

- **Techno-Economic Analysis of Alternative Configurations:** Investigate various hybrid microgrid configurations by changing the mix of renewable energy sources, storage capacity, and backup generator options. Investigate how various configurations affect the system's economic feasibility, dependability, and environmental effect.

- **Long-Term Performance Assessment:** Monitor and evaluate the performance of hybrid microgrid systems in rural areas over time. Examine aspects such as system deterioration, maintenance requirements, and response to shifting energy demand patterns to get insight into long-term sustainability and operational efficiency.

- **Community Engagement and Social Impact Assessment:** Conduct extensive research into the social and behavioral elements of energy availability and use in rural areas. Investigate how community participation, awareness campaigns, and user education programs might affect energy consumption patterns, encourage energy saving behaviors, and improve people' overall socioeconomic well-being.

- **Policy and Regulatory Frameworks:** Investigate the role of policy and regulatory frameworks in promoting the adoption of hybrid microgrid systems in rural regions. Evaluate current regulations on renewable energy integration, grid connectivity, tariff structures, and financial incentives to find impediments and potential for scaling up sustainable energy solutions.

- **Smart Grid Technology Integration:** Look at how smart grid technologies, advanced metering infrastructure (AMI), and demand-side management (DSM) methods may be included into hybrid microgrid systems. Learn how smart grid technologies can optimize energy distribution, balance supply and demand, and improve system efficiency while providing users with real-time energy data and control capabilities.

- **Environmental effect Assessment:** Conduct thorough environmental effect assessments (EIAs) to determine the ecological footprint of hybrid microgrid installations. Evaluate the lifetime emissions, resource consumption, land-use implications, and possible ecological consequences of renewable energy deployment, battery disposal, and diesel generator usage.

- **Resilience and Disaster Preparedness:** Investigate the resilience of hybrid microgrid systems in the face of natural catastrophes, severe weather, and other emergencies. Evaluate the system's capacity to keep vital services running, supply backup power during outages, and contribute to community resilience and disaster preparedness initiatives.

Addressing these research areas will allow scholars, policymakers, and practitioners to advance the understanding and implementation of sustainable energy solutions for rural electrification, thereby contributing to socioeconomic development, environmental conservation, and energy access for underserved communities such as Kikwit.

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