DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

University of Strathclyde Engineering

Investigation On Energy Diversification for Malawi Electrification

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ABSTRACT

Malawi's power generation and supply sector is facing serious challenges due to its heavy reliance on hydropower. The growth rate in power generation is much lower than the population growth rate, which has hindered industrial growth and discouraged economic investments. With an electrification rate of only 15% for a population of 21 million, the situation is concerning. Although the government has developed policies and plans over the years to improve electricity generation, access, and supply, many have not been fully implemented. It is time to put these policies into action to increase electrification levels. The study highlights the need to diversify energy sources and the importance of decentralized systems, such as microgrid designs, to improve electrification, especially in rural areas far from the main grid.

The study aimed to find the optimal combination of energy sources to improve energy access and security in Malawian communities. It used a case study of a small community in Mlangali Village, Kasungu District, located 15 km northwest of Santhe Township, to design a microgrid using HOMER software. The software simulated various scenarios to assess economic factors, security, and environmental impacts, particularly greenhouse gas emissions. HOMER software helps simulate and optimize systems with the lowest net present cost to find the best microgrid design.

The study found that the optimal system includes solar PV, battery storage, and a dispatchable generator to enhance security. This system achieved a 97% renewable fraction, reduced carbon emissions by 97%, met load demand with no shortages, and produced 4.66% excess energy. It was the best among all simulated scenarios, offering the lowest levelized cost of energy, net present cost, and capital expenditure.

Sensitivity analysis showed that changes in discount rates affect system costs, particularly net present cost, levelized cost of energy, and greenhouse gas emissions. Overall, the chosen scenario could serve as a model for power supply in many Malawian communities due to its economic affordability and cost-effectiveness.

ACKNOWLEDGEMENT

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Finally, I would like to acknowledge the Commonwealth Commission and Strathclyde University for awarding me the Masters Scholarship, which made this research possible. Their financial support has been crucial to the completion of this project.

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ACRONYMS

EGENCO- Electricity Generation Company Ltd.

ESCOM- Electricity Supply Corporation of Malawi

BESS- Battery Energy Storage System

PV- Photovoltaics

USAID-United States Agency for International Development

GoM- Government of Malawi

MERA- Malawi Energy Regulatory Authority

SE4ALL Sustainable Energy For all

DG- Diesel Generator

GHG -Greenhouse Gasses

RES/RE- Renewable Energy Sources/ Resources/Renewable Energy

DoD- Depth of Discharge

LCOE- Levelised Cost of Energy

NPC- Net Present Cost

1.0 INTRODUCTION

1.1 Problem definition

Malawi is a landlocked country found in southern east of Africa between latitudes 9^0 22’ S and 17^0 3’ S and longitudes 33^0 40’ E and 35^0 55’ E. The country is 900 km long and 81 -161 km wide with total area approximately 119000 km^2 of which 80% is land and the remaining 20% covered by water mainly Lake Malawi which is about 586 km long and 16-80 km wide [1]. The rest of the water covered by other small lakes and rivers. The country has a population of over 20 million as of 2022 with 19% concentrated in urban areas and 81% in the rural areas [2,3]. The country is divided in three main administrative regions namely Northen, Central and Southern region.

Malawi power generation largely is a clean form of energy mainly hydropower which was first commissioned in 1966 at Nkula power station on Shire River southwestern part of Malawi. Following this development were other hydropower plants installation at Tedzani, Kapichira both in southern part on Shire River and Wovwe hydropower station in the northern region on Wovwe river found in Nyika National Park with combined installation capacity of 390.55MW as of 2024 from all hydropower stations [4]. Aside from hydropower generation Malawi also uses other means of power generation such as 1.3MW solar plant at Likoma and Chizumulu Islands on Lake Malawi and diesel generators which adds 53.2MW to the National Grid [4].

Today, Malawi is still one of least electrified countries in the world, with only 15% of its population has access to electricity connection to the grid with 3% in rural areas and 48.7% in urban areas [2,5]. Malawi ‘s heavily dependence on hydroelectricity, has met so many challenges such as tropical cyclones and drought for the past decade mainly due to weather and climate changes which has caused the company to spend more money every year towards emergency rehabilitation projects [6]. For those connected to the grid, insufficient generation capacity and unreliable infrastructure cause frequent and prolonged load shedding across the country [7]. For example, in 2016 and 2017 due to low rainfall which led to low water levels in the Shire River resulted in insufficient power generation in hydropower stations. This caused frequent and prolonged power outages where in some areas they could spend more than a day without electricity [2]. Unreliable power generation and supply hampers economic growth of the nation as it slows down the growth of mining sector and industrialisation which are great consumers of power and pillars of economic growth of every developing nation [8].

Malawi has both short term and long-term vision to improve power access, security and reduce carbon footprint through clean energy generation drafted in Malawi's Vision 2063 which is in line with Sustainable Development Goals (SDGs) especially SDG 7 which says "Clean and Affordable Energy for All" [9]. The short-term plan is to increase the current electrification rate to 30% by year 2030. This will see the number of homes electricity connections from 1.5 million to 5 million homes through grid expansion [10]. It is of this reason that the dissertation will focus on investigating the possible energy resources mix to improve electricity access, and security targeting technologies with low carbon emissions. This thesis will focus on energy resources that are used for generating electricity.

1.2 Aim.

The aim of the project is to investigate possible combination of energy generation resources to improve energy access, energy security for Malawi communities and country as whole focusing on clean energy technologies to reduce carbon emissions in line with Malawi's Vision 2063.

1.3 Objectives

1. Develop a broad understand of Malawi current and future energy consumption and needs.
2. Develop a broad understanding of current Malawi energy supply and transmission.
3. Analyse possible power combinations to improve electrification levels, including an analysis of energy costs through Microgrids.
4. Evaluate the pros and cons of energy generation resources mix available that could improve access, security, help reduce carbon emissions and shape the future of electricity access and security in Malawi.

1.4 Overview of Methodology.

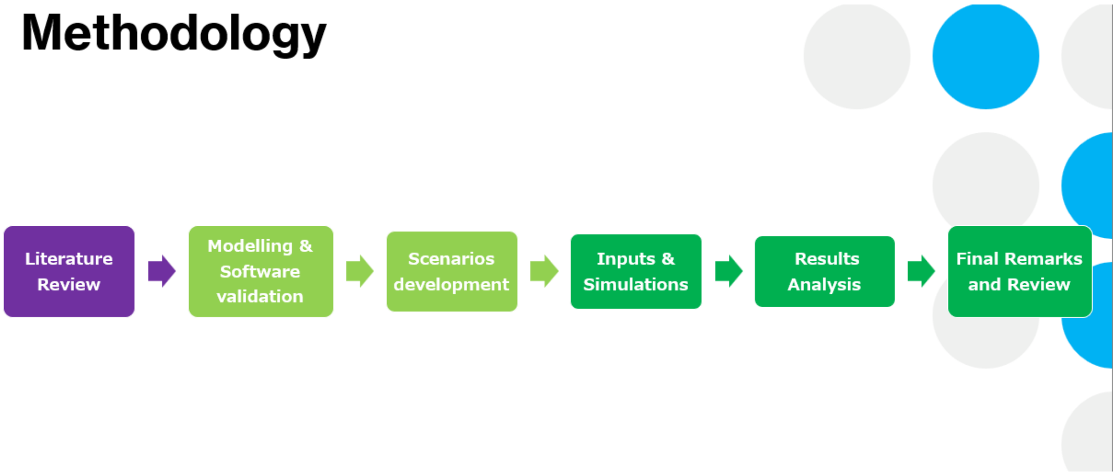

Figure 1: Thesis Methodology

2.0 LITERATURE REVIEW

2.1 Malawi Overview

Malawi is in southern east Africa which shares borders with Mozambique to the east spanning up to southwest, Zambia to west and Tanzania to the north (See Figure 2). The country population is estimated to be over 20 million as of 2022 with annual growth rate of 2.6% [1]. Malawi is still struggling with development despite making structural and economic reforms to sustain growth [2].

Malawi generates 90% of its power from hydropower plants with combined installation capacity of 390.5MW which is topped up with 53.2MW from diesel generators and solar power making total national grid capacity of 444MW [4,5]. Power is generated by Electricity Generation Company Ltd. (EGENCO) and is sold to utility provide Electricity Supply Corporation of Malawi (ESCOM) which sale the power to consumers. With lowest electrification rates in the world at 15% and frequent blackouts and brownouts lasting up to 25 hours [3,13], 97% of the households rely on solid fuel for cooking such as charcoal and firewood which has resulted into environmental degradation contributing so much to climate change which in turns also affect hydro power generation [5]. It is also important to note that due unreliability of the national grid electricity about 40% of urban households use charcoal for cooking which is leading deforestation adding strain on climate change fight [1]. Energy transmission exceeds energy supply by 170% with large deficit in supply [5].

Figure 2: Location of Malawi. Source[14]

2.2 Current Energy Situation in Malawi

2.2.1 Power Generation and Ownership

Malawi electrical power generation and distribution companies are state owned. Power is generated by Electricity Generation Company Ltd. (EGENCO) from hydropower stations, diesel generators and solar power which is distributed and sold by utility company Electricity Supply Corporation of Malawi (ESCOM) to consumers [15]. Previously ESCOM handled both generation and distribution before it was unbundled in 2017 [4]. EGENCO operate four river run-off hydro power plants at Nkula, Tedzani, Kapichira located on Shire River in southern part of Malawi and Womwe in Wovwe river northern part of Malawi which feed 99% of its power to the national grid of which 98% of it is generated in Shire River. Nkula hydropower plant commissioned in 1966 with 8 machines generating total of 135.10MW power was the first major power generation project followed by Tedzani Hydropower with 4 stations and 7 machines generating 121.1MW of power. Kapichira power station has total of 4 machines generating 129.6MW and Wovwe power station generate 4.35MW [4]. Added to the hydropower plants, Egenco also operate diesel generators during peak hours and emergency situations with 20MW installed at Mapanga Blantyre, 20MW installed at Kanengo, 5.4MW Lilongwe A, 6MW installed at Luwinga in Mzuzu and 1.8MW together with 1.3MW solar power plant coupled with battery storage facility at Likoma and Chizumulu Island totalling to 53.2MW [4]. The total power Installation capacity under EGENCO is 441.55MW and available power is 384.15MW [4].

According to 2022 Malawi ministry of energy statistics overview, the national grid is also fed with 8.2MW from Mulanje Hydropower which supplies power to Mulanje and Thyolo district residents [6]. Golomoti Solar Photovoltaic (PV) and Battery Energy Storage Co-developed by Power Africa, JCM Power and the Private Infrastructure Development Group's InfraCo Africa, and with financial support from Innovate UK [7] in Dedza approximately 100 kilometres southeast of Lilongwe feed 20MW coupled with 5MW Battery Energy Storage System (BESS), JCM Power Salima solar plant feed 60MW [8] and Serengeti feed 21MW of power generated from solar [6] into the National grid. Malawi also import 20MW of power through Mozambique-Malawi cross border and 7MW through Zambia-Malawi cross border at total of 27MW imported electrical power.

The Figure 3 below is the summary of power generation and supply in Malawi which is dominated by Hydropower.

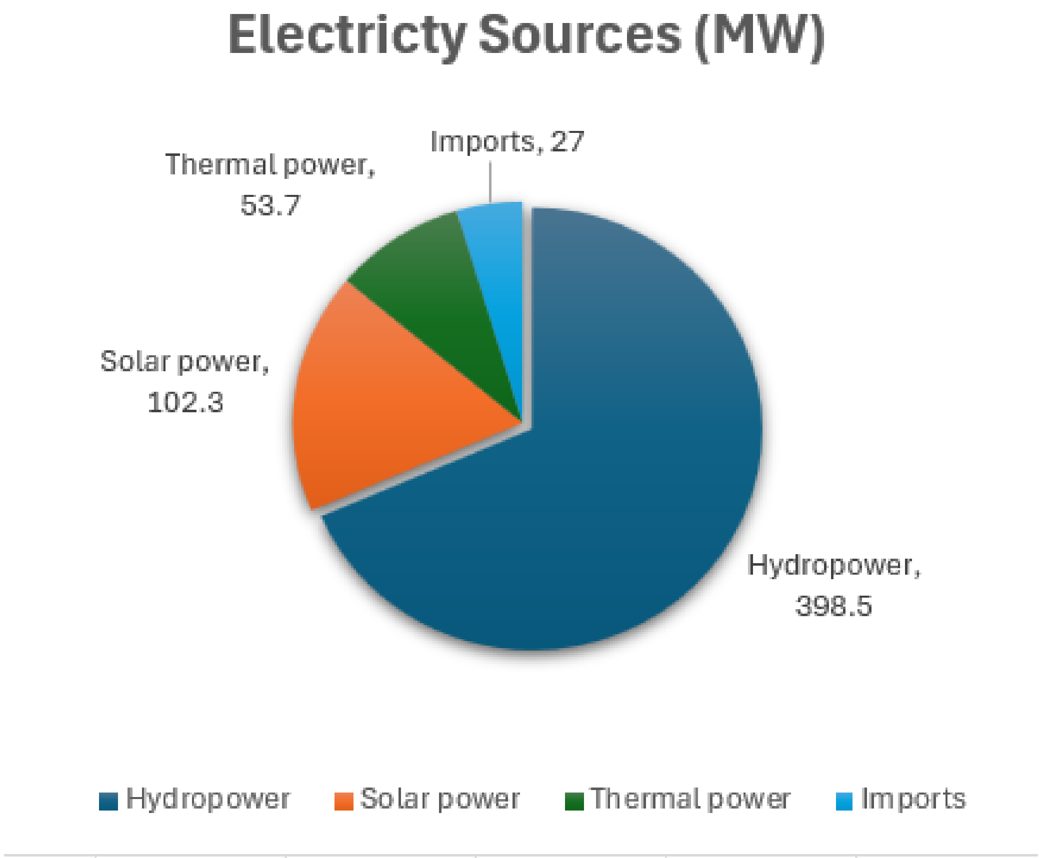

Figure 3: Malawi Power Generation Profile. Source [16]

The government also started recognising other Independent Power Producers (IPP), for instance in its report produce by Malawi Energy Regulatory Authority (MERA) produced list of sources of electricity generation including off grid systems that are owned by sugar production companies that use bagasse [19]. The Table 1 below provide details of all generation stations which are recognised by MERA.

Operator	Plant name	Net capacity (MW)	Operation date	Energy type	Notes
EGENCO	Nkula A	35.1	1966	Hydro	
	Nkula B	100.0	1992	Hydro	
	Tedzani I	20.0	1972	Hydro	
	Tedzani II	20.0	1976	Hydro	
	Tedzani III	62.0	1995	Hydro	
	Kapichira Phase I	64.8	2000	Hydro	Kapichira offline in 2022 due to a storm
	Kapichira Phase II	64.8	2013	Hydro	Kapichira offline in 2022 due to a storm
	Wovwe	4.4	1996	Hydro	
	Tedzani IV	19.1	2021	Hydro	
	Mapanga	20.0	2018	Diesel	
	Luwinga	6.0	2017	Diesel	
	Kanengo Phase I	10.0	2016	Diesel	
	Kanengo Phase II	10.0	2019	Diesel	
	Lilongwe A	5.4	2016	Diesel	
	Likoma	1.2	2019	Diesel	
	Chizumulu	0.7	2019	Diesel	
	Likoma	1.0	2020	Solar	
	Chizumulu	0.3	2020	Solar	
	Total	**444.7**			
IPP	Mulanje Hydro	8.2	2018	Hydro	
	Cedar Hydro	3.0	2022	Hydro	
	Aggreko	78.0	2017	Diesel	Contract ended in March 2022, capacity not included in totals
	JCM Salima	60.0	2021	Solar	
	Golomoti	20.0	2022	Solar	
	Total	**91.2**			
Autoproducer	Dwangwa	18.0		Bagasse	
	Other autoproducers	17.0		Mixed	
	Total	**35.0**			

Table 1: Power Generation Stations & Current Status. Source [19]

Despite adding some new sources of electricity in past few years Malawi is still struggling to meet the demands of electric power. From Figure 4 Malawi power generation is still lacking behind when compared to the other nations in the region and times the generation keeps dwindling no significant growth has been seen for the past two decades. This may be the result of poor power infrastructure growth, harsh climate changes such as tropical storms like cyclone Ana [20] which have affected hydropower generation and policy and regulations hurdles.

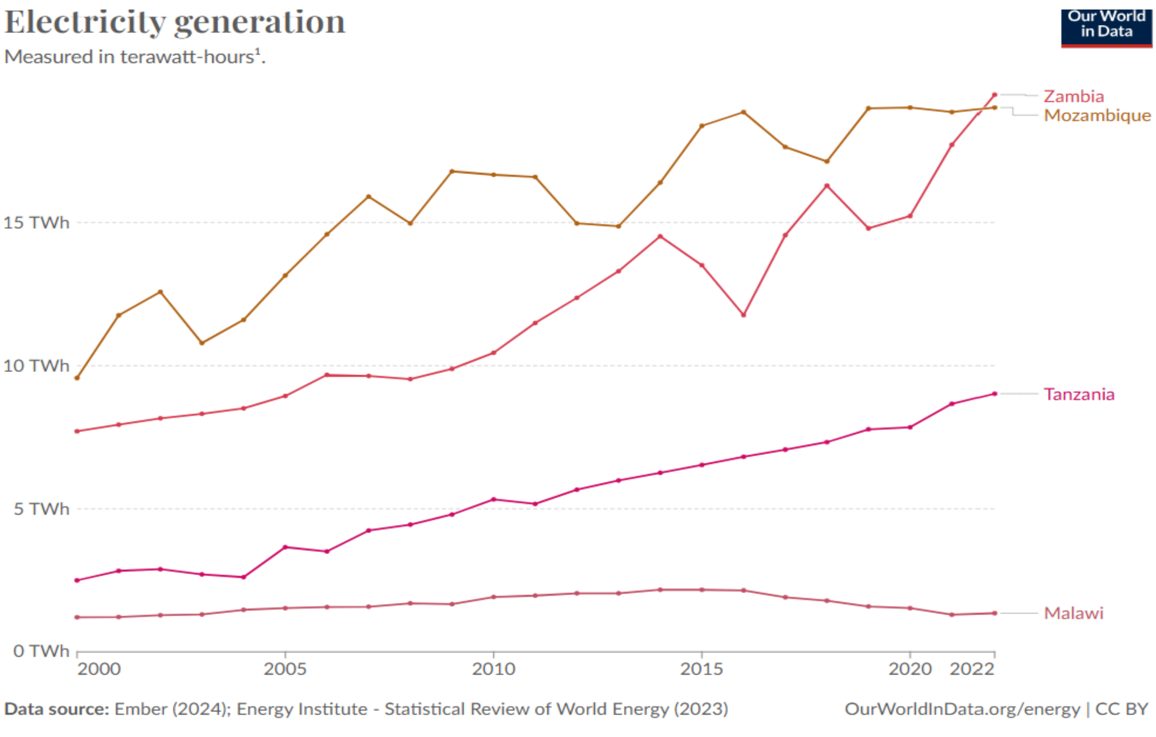

Figure 4 : Electricity generation profile for Malawi and Neighbouring Countries Source [21]

2.2.2 Cost of power generation, transmission, distribution and use in Malawi.

The cost of energy in Malawi varies significantly depending on the source of generation, transmission and distribution including taxes imposed by the Malawi Revenue Authority (MRA). The cost of hydropower generation (main source) is largely affected by aging infrastructure making it susceptible to climate and weather challenges such as tropical cyclones, which require frequent repairs to continue producing electricity [5] . This is the reason why cost electricity is high in Malawi compared to other sub-Saharan African countries such as Mozambique, Kenya and Tanzania. Currently ESCOM residential tariff is $0.064/kWh, this is national level tariff and subsidised by the government and power residential cost for Mini grid solutions is rated at $0.45/kWh, which is much higher compared to ESCOM mainly due high financing costs [10]. Transmission and distribution lines are old which have also added extra costs for repairs, power transmission and accounted for more power losses estimated at over 14%. No official documentation in terms of power generation cost, transmission and distribution as most documents just include the cost selling to final consumers.

2.2.3 Energy Policy and Access

For a country to improve energy access and security it needs to have good polices and regulatory framework which will help attract the investors in the sector because the primary concern of investors is the effectiveness of the energy regulatory framework [10]. Malawi energy Policy focuses on increasing affordability and reliability of energy national wide by reaching 80% electricity access by 2035 through new power investment focussing on renewable energy sources [11]. The policy stipulates its focus on shifting electricity dependence from centralised connection model to Mini grids systems and allow private sector investment [11]. The National energy Policy 2018 also aims at increasing the renewable energy mix from 10% to 23% by 2030. In this regard the Government developed Renewable energy strategy to increase electricity access to over 80% of Malawians living in rural areas [23] The policy includes other provisions related to increasing number of microgrids in order achieve its targets, these provisions include supporting small scale renewable energy initiatives by communities or entrepreneurs, capacity building in areas of renewable energy technologies programming, supply and services. The policy also includes other provisions on promoting private investment driven renewable energy technology projects and financing off-grid solutions through infrastructure development, subsidising tariff costs to promote access and affordability of electricity [19,24]. The policy includes Malawi government to allow plans for different types of partnerships which include community-based partnerships.

In terms of energy access, Malawi relies on biomass energy for cooking and heating consisting of 86% of country overall energy use, 10% from oils, electricity only makes up 3 % and 1% from coal [6]. Though Malawi has managed to come with policies to improve access in the past years the results have not shown much improvement. From the data obtained from World Bank it shows that Malawi has lowest percentage of electricity access when compared to other East African countries such as Mozambique and Ethiopia. From the Figure 5 electricity access of Mozambique and Malawi were almost the same in year 2000 but Malawi is struggling to improve its access over the period of 20 years when compared to other countries. Possible reasons to this trend may be high population growth, limited growth of power infrastructure, over dependency on hydropower which resulted into slow growth in other forms of energy [10].

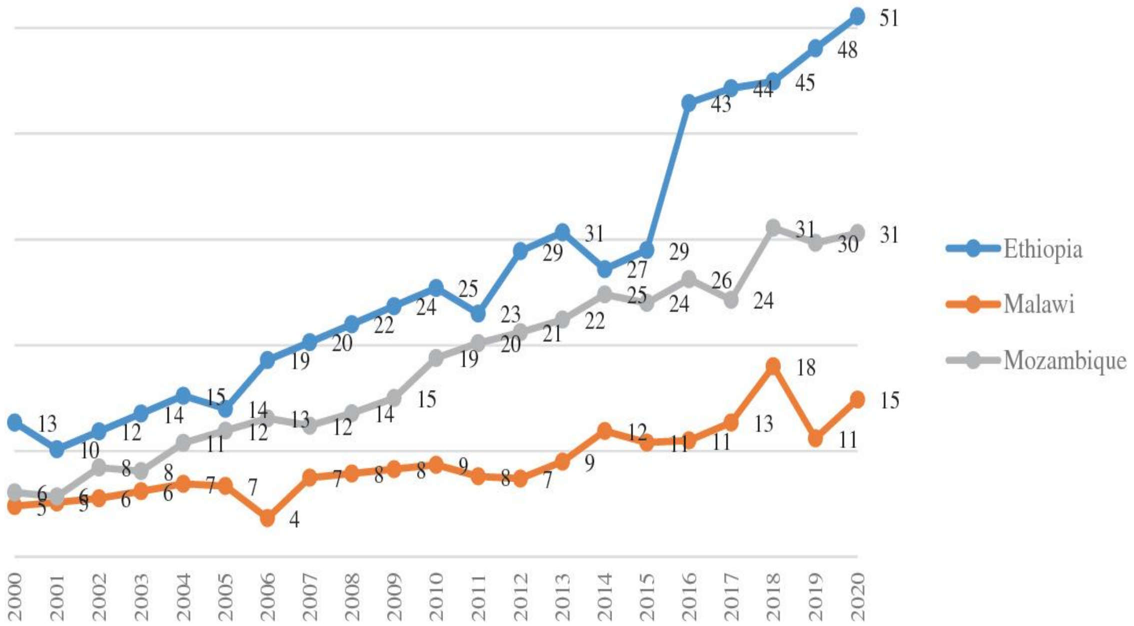

Figure 5: Energy access levels for Malawi, Ethiopia and Mozambique. Source [10]

Malawi today still faces power shortages. The electricity generated is not enough to meet the demand of growing population which has made ESCOM to resorts to loadshedding program to manage available electricity [15]. The limited electric power infrastructure development has affected Malawi economic growth which has deterred many industrial investments from foreign investors [14].

2.2.4 Energy security

Energy security is abroad topic with critical importance to many different stakeholders including policy makers, business and communities whose quality of life is dependent on uninterrupted supply of energy [26]. The wide accepted definition of Energy security is based on the idea of an uninterrupted supply of power. However, the topic is also more related to access to the supply, and it includes issues of reliability, affordability, sustainability and environmental acceptability of energy supplies [27]. The performance metrics from energy security can be used to ascertain whether energy policies adopted are effective or they need to be revised [28]. Thus, energy security is used as the measure of country power generation industry performance and growth.

Malawi continues to experience low access to electricity in the Sub-Saharan Africa compared to other nations. The country reliance on hydropower has met a lot of challenges including vulnerability to climate changes such as drought and tropical cyclones such as Anna in 2022 [29] which result in prolonged national blackouts [30].

2.3 Previous Studies on Energy Supply in Malawi

There are not many studies done concerning energy supply situation in Malawi, one notable paper worth discussing was published in 2015 titled “Energy Supply in Malawi: Options and Issues” [8]. In this paper John L. Taulo et al. discussed that insufficient energy supply is still a significant challenge, affecting social, economic and industrial development of the country pointing out overdependence on hydropower as one of the major reasons. The paper highlighted critical issues such as aging infrastructure citing that over 50% of Malawi power generation Plants including transmission and distribution lines have surpassed their expected life span causing frequent maintenance requirements, blackouts and power generation and transmission inefficiencies. Another critical issue discussed is related to operation challenges emerging from climate and environment issues likely caused by extensive deforestation such as low water levels, siltation, floods, droughts which in turn affected generation capacity. The increase in deforestation was mainly due to dependence on charcoal and firewood for domestic heating and cooking. It is also worth noting that the paper discussed the potential on energy diversification as one of strategies to deal with energy supply issues citing the possibility of coal plant using local coal as fuel, wind, solar and pumped hydro as some of the measures.

The second paper worth discussing was published by Kaunda. C.S et al. titled “Energy situation, potential and application status of small-scale hydropower systems in Malawi” [31]. This paper discussed the dominance of traditional biomass forms for domestic usage, low levels of modern energy supply and unreliable and low electricity supply as some of issues Malawi is facing. The paper further discussed possibility of having decentralised (off grid) power systems for rural areas using small hydro power plants to improve access and help reduce over dominance on biomass hence reducing deforestation a net gain in fighting climate change. The paper concluded with some remarks on policy reforms aiming at increasing access and energy security.

2.4 Energy Diversification

Diversification is a complex term which has been used and applied in various fields of study including science and technology. The main element of its fundamental application lies in its meaning which may mean risk reduction by variable solutions, adding flexibility during implementation of various processes and resources utilisation [32]. In brief energy diversification means the use of various energy resources to generate power to avoid sole dependence on one or very few energy resources [33]. Previously diversification was more common in business related publications but recently the term diversification has been used in energy related publications more compared to business publications which shows the significance of term diversity in energy industry as it relates to energy security [32].

Energy mix diversification has also been recognised as an emerging strategy for developing economies to achieve energy security targets and meet net zero carbon emissions by 2050 [34][34]. The strategy would help to ensure sustainable and secure energy supply which involves the use of diverse mix of energy sources including both renewable and non- renewable resources to reduce risks associated with overdependence on one type of energy source there by enhancing energy security, environmental protection and economic stability [32]. This means that with energy diversification, country ‘s energy security increases such that failure of one energy source will not have much effect on its economic stability and it offers preventive measures against shocks in energy supply system, and it ensures adaptiveness in times of uncertainties [35,36]. It is said that; “it’s better to be exposed to several risks which have limited consequences than single risk where probability of failure is weak, but that failure has unbearable consequences for the economies” [37].

The Figure 6 shows top African Economies showing different levels of power diversification with Kenya being the top diversified and secure as it has good balance of power generation from different energy sources. Countries like Algeria and Nigeria though having high energy access they are likely to suffer the worst consequences because of they over dependence on natural gas.

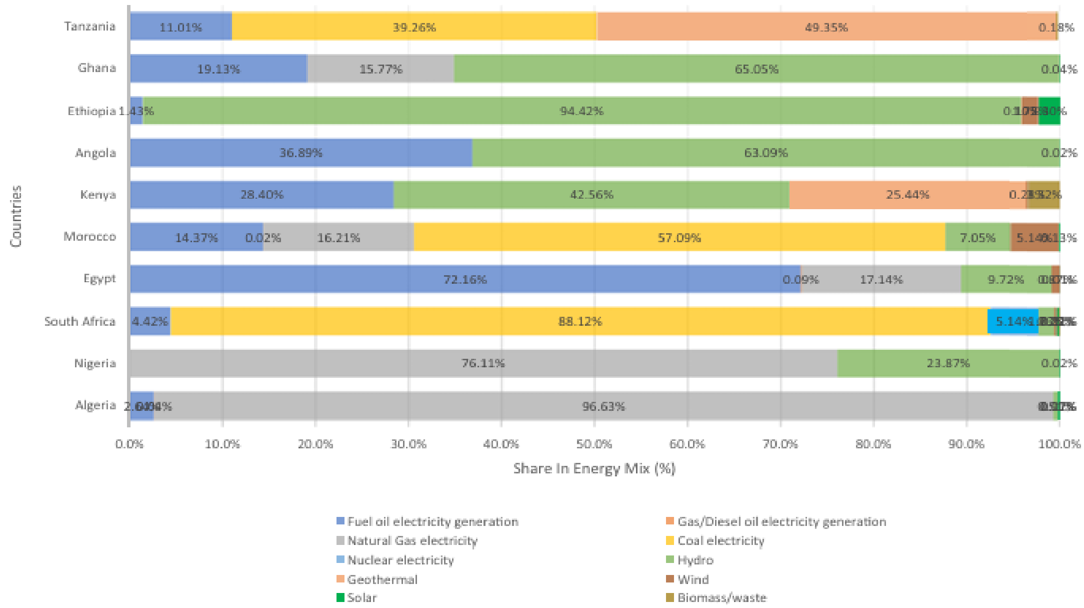

Fig. 4 Total shares of electricity generated from each source as at 2017 (Source: Author's construct, created with Microsoft Excel)

Figure 6: Top African Economies Energy Diversification. Source [36]

Another benefit of energy supply diversification is that it improves energy access. In countries where access to energy is low especially in Africa energy security is likely to be low. More power generation sources would mean high generation capacity, access and uninterrupted to supply of power [35,36]. Azzuni and Breyer study [38] about global energy security shows that most energy diversified countries like Kenya have high energy security and access when compared to other countries' economies with less power diversification. Malawi overdependence on hydropower is an example of less diverse nation in terms of power sources which has suffered dire consequences during dry spell when water levels are not enough to generate enough power and with aging infrastructure getting damaged during tropical cyclones resulting in prolonged blackouts, loss of funds through rehabilitation projects.

2.5 Energy Resources

2.5.1 Renewable Energy Sources

2.5.1.1 Solar PV

Malawi is in tropical region closer to the equator. The geographical location makes it experience a lot of sunlight throughout the year. Mean horizontal solar radiation is 5.8kWh/m^2 per day [14,39]. The Figure 7 below shows the potential of Solar power in Malawi which can go up to 7kWh/m^2/day. According to the Zalengera et al, "if 2% of landmass is utilised for solar generation Malawi would generate around 6000GWh per year at 15% efficiency module which is more than three times generated by hydropower in a year which is 1900GWh" [14]. This shows the potential of solar power in Malawi that can be added to national generation capacity and improve power access and security.

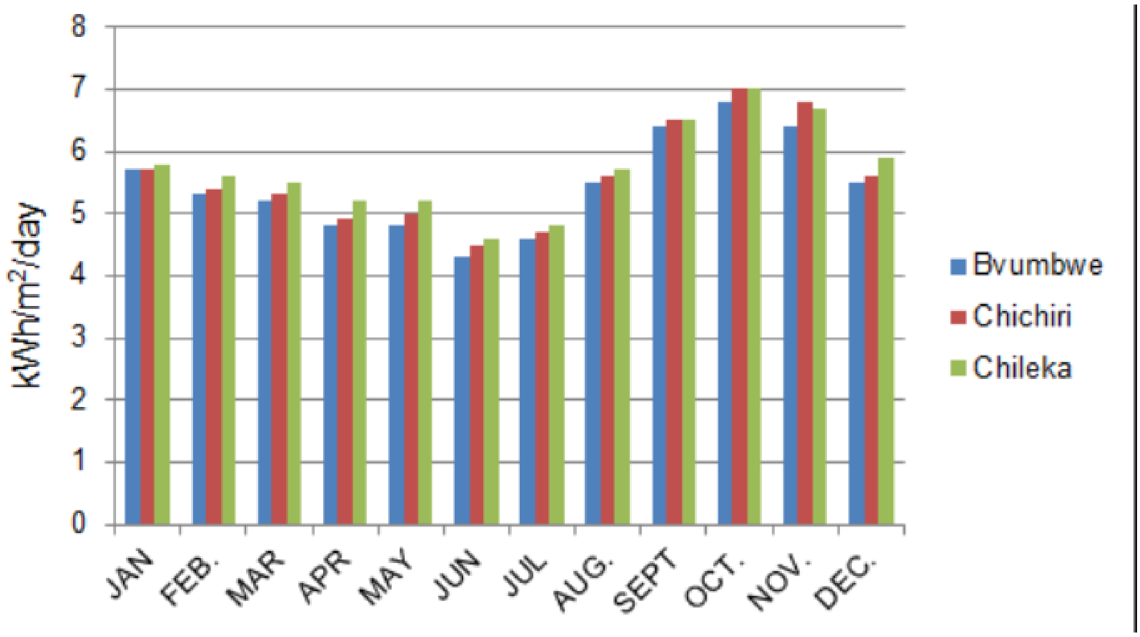

Figure 7: Daily Mean Solar Radiation From 3 Weather Stations. Source [14]

Solar energy can be harnessed using both photovoltaics to generate electricity for grid distribution and solar thermal which is used for direct cooking and heating. Currently there is notable growth in solar power implementation. In 2022 the Malawi commissioned 60MW Salima solar PV power plant and Dedza Golomoti 20MW which marked new milestone in renewables [40]. There has also been development in microgrids implementation in rural areas with aim improving electrification levels. One notable example is the Rural Energy Access through Social Enterprise and Decentralisation (EASE) project implemented by University of Strathclyde [41,42].

2.5.1.2 Hydropower

Malawi has potential rivers such as Shire, Bua, Dwangwa, etc. including Lake Malawi which are feasible locations for hydropower generation [43]. Current major existing hydropower plants are river runoff on Shire River which is an outlet of Lake Malawi and branches into Zambezi River in Mozambique [44]. Hydropower has been main source of electric power for over 50 years in Malawi. Although been in operation for longtime the resources are still considered underexploited as it is considered to have potential of generating 1.34GW more in addition to the existing capacity [14]. As previously discussed, hydropower generation has met several challenges emerging from climate changes such as droughts, floods due to cyclones which has led to poor access and reliability [20,45].

There is potential for pumped hydropower generation. The runoff river hydropower system does not fully utilise available water for power generation during rainy season when water levels are high with large water discharge [44]. The hydropower power plants are not optimised to handle such peak discharge, and they suffer low discharge during dry season which affect amount of power produced. There is potential of having large Reservoir dams where water is pumped and stored during peak discharge to be used off peak discharge to ensure continuous uninterrupted supply of power [43,44].

2.5.1.3 Wind power

Malawi has potential for onshore wind power generation. According to wind data obtained from the department of Climate and Meteorological services shown in Figure 8 below at 2m height wind speed in the selected areas for one year between 2005 and 2008 which showed that the peak speed of the wind reached 6.6m/s in Chitipa and were high in months of July and until October. The wind speeds shown in the diagram are practical for small scale applications probably at hub heights of more than 10m above ground to minimise effects of sheltering and terrain roughness at elevated heights [14].

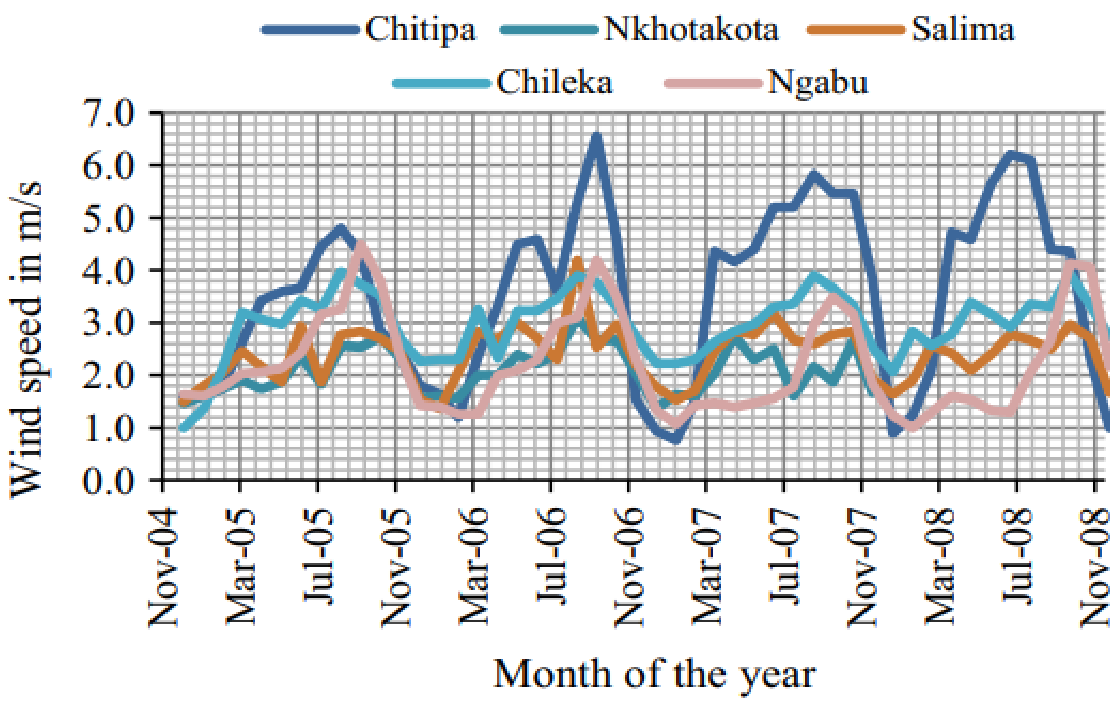

Figure 8: Monthly Mean Windspeeds at 2m Height Weather Stations. Source [14]

This data does not entirely give exact windspeed potential of the country as most studies in weather stations have only 2m tall and the reliance on reanalysis datasets potentially leading to inaccurate results [40].

Grain P.M, Minerals, Geology, Environment & Corporate Affairs Consultant in his report "Wind Energy Potential in Malawi" described three sites Lilongwe, Blantyre and Mzuzu that have potential of installing wind turbines ranging from 2MW to 5MW each proving the viability of wind energy generation [46]. A feasibility study conducted by Malawi Government under Ministry of Energy at Lunjika Mzimba district northern region showed that wind farm consisting of 29 V126, 3.6MW turbines could be designed with total capacity of 104MW and annual energy of 510GWh/y [47].

2.5.1.4 Biomass

Biomass is the most common consumed source for energy for majority of the households account for over 80% of Malawians depending on the traditional biomass sources such as firewood, forest residues and agricultural residues home cooking and heating [1]. Recently there has been high production of charcoal as source of cooking and heating and increasing demand in urban places most houses rely on charcoal for cooking and heating standing for 46% of total demand of charcoal [48].

Residues from sugarcane have been used by sugar producing companies as source of electricity for their operations. For instance, companies like Salima Sugar company, Illovo Sugar Company both Ntchalo Chikwawa and Dwangwa use sugarcane bagasse to produce electricity for company production operations and electrifying surrounding communities. The two Malawi Illovo production factories produce 950 tons of bagasse that has potential of generating 62MW of electricity but produces only 18MW limited by the equipment installed [19,49]. Scaling up these sugar industries to increase production and generate enough to supply to the communities would greatly increase power access.

2.5.1.5 Geothermal Power

Malawi has several potential geothermal sites with a good number of them found in northern region such as Chiweta in Rumphi district[50]. More than 20GW of geothermal sources are estimated to be available for the Great East African Rift valley system with Kenya having greatest potential generating around 600MW. Malawi is one of the countries in southern east Africa found within the East African Rift Valley with great potential utilising geothermal resources [51] with potential of 200MW that can be generated [52]. The project has not been. The project has not been implemented with absence of both technical and financial ability being some of the reasons [53]. Feasibility studies carried out by the government under Ministry of energy recommended implementation of First phase 10MW Chiweta geothermal project with estimated $76.2 million as capital investment including exploration costs translating to $7600/kW and tariff estimated to be at $0.104/kW which is cheaper than the current electricity tariffs [54]. Implementation of this project will greatly improve electricity access.

2.5.2 Non-Renewable Energy Sources

2.5.2.1 Diesel Power Generators

Current power generation capacity includes 53.7MW of power generated from diesel generators deployed in different locations as previously discussed operated by Egenco [4]. Diesel generators re good source of power in off grid areas and isolated places and for emergency situations but the project has proven to be very expensive to operate and requires high capital expenditure to procure the generators. The project has also come under scrutiny by environmental activists concerning emissions levels as compared to other forms power generation like hydropower, wind and solar.

2.5.2.2 Coal Fired Plant

Malawi has estimated coal reserves between 80 million and 1billion tons of which 20million are proven reserves of bituminous type. The quality of the coal varies with energy content ranging between 17 to 29MJ/Kg [1]. Despite having large reserves of the coal, the country has only two active mining sites of which the produced coal is not sufficient to sustain industrial activities and to supplement the demand the balance is imported from Mozambique [1].

There have been efforts by the government to build 300MW coal fired plant at Kammwamba in Neno district with plans to import extra coal from Mozambique for the plant operations to reduce over dependence on hydropower from 95% to 76 % in five years and increase power access. Feasibility studies were done between 2019 and 2021, but the project is yet to start, with financial capacity being one of reasons for delay [55]. The project has also come under strong criticism from environmental activists and developed countries such as United Kingdom urging Malawi to rethink its plans for building coal fired plant [56]. Victoria R, Narule in her paper “Transitioning to Low Carbon Economy: Is Africa ready to Bid Farewell to Fossil Fuels?” explained the disparities that exist between developed countries who have benefited so much from fossils fuels and developing countries who are struggling to meet the basic power demands. The paper emphasized that even resources rich-developing countries meet significant challenges in transitioning to clean energy forms. This process is even more challenging for developing nations. This process is even more challenging for developing nations [57]. These issues have become notable challenges that developing countries are facing when it comes implementation of non-renewable power generation.

2.5.2.3 Nuclear power

Malawi has 63000 tons proven reserves of uranium at Kayerekera in Karonga district and other areas yet to be quantified. Mining began in 2008, but all the mined uranium was transported outside country because the country has no uranium processing plant. Though the government showed interest in erecting nuclear power plant in future, there are no notable progress or plans made so far on the development [1]. Though being clean form of energy, nuclear energy has become less popular in recent years as the rate of nuclear power plant additions has been outpaced by new advanced technologies probably because of heavy capital investment at both implementation and decommissioning stages as well as waste treatment [58].

2.6 Case Studies

This will explain some examples of case studies where energy diversity was applied and how it has helped their economies. The case studies were obtained from [59] and [36].

- **The Case of Nordic nations (Denmark, Finland, Norway and Sweden** [59]**.**

The Nordic nations are highly diversified nations in terms of power generation which is highly accumulated with renewables. In this study data on power consumption and generation from 1998 to 2018 was used establish the link between energy resources diversity and increased economic activity. The research used experimental models to evaluate the impact of the energy mix has while simultaneously controlling other factors. The results concluded that the increase of energy resources has over course of time a considerable and positive impact on fostering economic growth. The paper further argued that there is no evidence that energy diversification has negative impact on economic performance over long period and the adverse effect of energy diversification on economic growth are temporally. The paper concludes with positive contribution of energy mix to sustainable development objectives under Sustainable Development Goals (SDGs) in achieving affordable and clean energy for all and climate change action.

- **The case of Africa's largest economies** [36]

The research paper used the Energy Mix concentration Index method (EMCI) to study energy diversification of the African top ten economies over the period of 18 years using power generation data from 2000 to 2017. The results showed that diversification was occurring at a very slow pace with Kenya and Morocco being the most diversified nations with EMCI index 0.34 and 0.37 respectively. Algeria and Ethiopia ranked the least diversified with EMCI index o.98 and 0.87 respectively. The study also established that energy mix trends were consistent with multiple energy stacking model rather than energy ladder hypothesis which uses share of each energy resource in the energy mix to establish diversification. In contrary to past trends, the study established that energy diversity is not just the number of sources in the energy mix but the share of each source in the mix. For instance, South Africa, Algeria and Egypt have more varieties of the mix but have high indices 0.81, 0.98 and 0.53 respectively which shows they are not more diversified compared to Kenya and Morocco which are more diversified despite having low varieties on energy sources but have considerable share in the mix. The study also showed the relationship between gross domestic product (GDP) growth and Energy Mix Concentration indices, which suggested that the increase in GDP means that the energy system mix is more diversified. The study concluded energy diversification is an important precursor for energy security and sustainability transitions and has the potential to improve access rates and energy security.

2.7 Challenges and Opportunities

This section briefly explains some of challenges and opportunities that comes with diversifying energy sources.

2.7.1 Challenges

1. Increasing share of energy mix in power distribution systems comes with its challenges. Different sources of energy are added into the system to provide high excess and energy security including high penetration of renewables such as solar and wind. Challenges arising from high renewables integration to power distribution network may cause voltage fluctuations, voltage rise, voltage balance and harmonics [60–63].

- Impact of PV integration into the distribution may cause unnecessary power excitation due intermittent nature of these renewables. These impacts are related to the voltage imbalances, harmonics that affect performance and reliability of the systems [62,63].
- Impact of wind penetration may increase the fluctuations which may result in severe frequency variations which makes frequency relays of wind turbines to be disconnected from the power system [64,65].

2. The other challenge associated with diversifying or increasing energy mix is related to economic viability of such projects more especially for the developing countries. The article on World economic forum[66] explained how difficult it is for developing countries to implement new energy mix projects due high upfront costs, limited access to technology, inadequate infrastructure and limited financial resources.

2.7.2 Opportunities

1. Energy diversification may help in mitigating the adverse effects of declining energy resources supplies and the impacts of international changes, such as wars [59].. For instance, the ongoing conflict between Ukraine and Russia has significantly disrupted gas supplies to several European countries, including the UK, which have historically depended on Russian gas for electricity generation. This reliance on a single source of energy has highlighted the vulnerabilities in the energy supply chain and underscored the need for a more diversified energy portfolio. By incorporating a mix of energy sources, countries can reduce their dependence on any single source and enhance their energy security [67]. This strategic diversification helps stabilize energy supply, manage risks associated with geopolitical tensions, and support a transition towards more sustainable and resilient energy systems.
2. Diversifying energy sources may help to reduce the influence of energy costs on items like prices of food and other tensions that may rise due to price volatility [59]. When a country relies heavily on a single energy source, fluctuations in the price of that energy source can have a ripple effect throughout the economy. For example, high energy costs can increase the cost of food production, transportation, and storage, ultimately leading to higher food prices. This price volatility can cause economic instability and social tension.
3. Energy diversity offers an opportunity not only to improve energy access and security but also to reduce carbon footprints through the integration of renewables [59].

Diversifying energy sources allows countries to rely less on fossil fuels, which are major contributors to greenhouse gas emissions. By incorporating renewable energy sources such as solar, wind, and hydroelectric power, countries can significantly lower their carbon emissions [59,68].

2.8 Microgrids and their roles in Electrification

According to United Nations report 675 million people still have no access to electricity of which 4 out of 5 of those people are found in sub-Saharan Africa [69]. The estimated universal power access by 2030 is estimated to cost more than $48 billion each year but the good new I that most renewable energy sources process are going down to facilitate the SDG7 which promote affordable and clean energy for all. Boche Antoine et al, in his paper title titled, “Understanding microgrid sustainability; A systematic and comprehensive review” recommended that decentralised power system approach is new emerging way which is more reliable and efficient for rural electrification because of its high versatility and lower costs [70]. Experts agree with an idea of using decentralised electricity networks capacity to power entire cities or medium sized regions by 240 [71] Despite extensive growth studies in this field there still extremely low uptake system in rural areas suggesting that financial hurdles being the main reason and lack of business interest from investors [70].

Microgrids play an important role in rural electrification where main power grid cannot reach. This technology could be the solution to the developing economies power access problems by providing clean and affordable electricity to rural communities [72].

Figure 9 below summarise the potential benefits of microgrids.

Figure 9: Potential benefits of microgrids. Source [70]

Microgrids represent a forward-thinking approach to powering the future, particularly in rural areas where main power grids cannot reach. They offer environmentally friendly technologies that promote sustainable practices. For Malawi, implementing microgrids could significantly benefit various communities by increasing electrification levels and reducing reliance on a single energy source, thus fostering a more diversified energy mix.

3.0 METHODOLOGY

To investigate the role of energy diversification for Malawi electrification this study will use microgrid modelling to show how different power generating sources can be used to provide electricity in remote isolated areas which are far from the nation grid connection point. This chapter will include the selected case study area, modelling and software adopted to model the microgrid.

3.1 Case Study

The chosen Area for this case study is a small Community within Mlangali Village found in Kasungu district Santhe area approximately 15 kilometres northwest of Santhe Trading centre located in the Southern Hemisphere of eastern Africa at 13°S latitude and 33°E longitude (see Figure 10). The community like many other communities has estimated 70 households and a Primary school and 10 business shops. This area has been selected using Malawi Integrated Energy Plan which list places with great need for microgrid implementation to improve electricity access [73]. The Malawi Integrated Energy Planning Tool (MIEPT) is a decision-support tool tailored to support decision makers on implementing projects aimed at improving residential and institution electrification. It was developed by ministry of energy and SE4All and was released in 2022 [74]. Providing electricity to this community would boost daily lives of people through small business-like barbershops, would also boost students' education by extending study hours, and grocery shops. It would also help the community stay connected to the internet by providing available power for charging electronic devices like smartphones and computers.

Kasungu district has the highest potential number of minigrids compared to other in central region with potential 319 minigrids out of 541 minigrids for the central region [73]. According to 2018 population census data Kasungu district covers 8,017km^2 with population over 847,000 [75] and very few areas have access to electricity.

Figure 10: Satellite Image of Mlangali Village. Source: Google Earth

The Figure 11 below show satellite image of the Kasungu district map with yellow boundary lines.

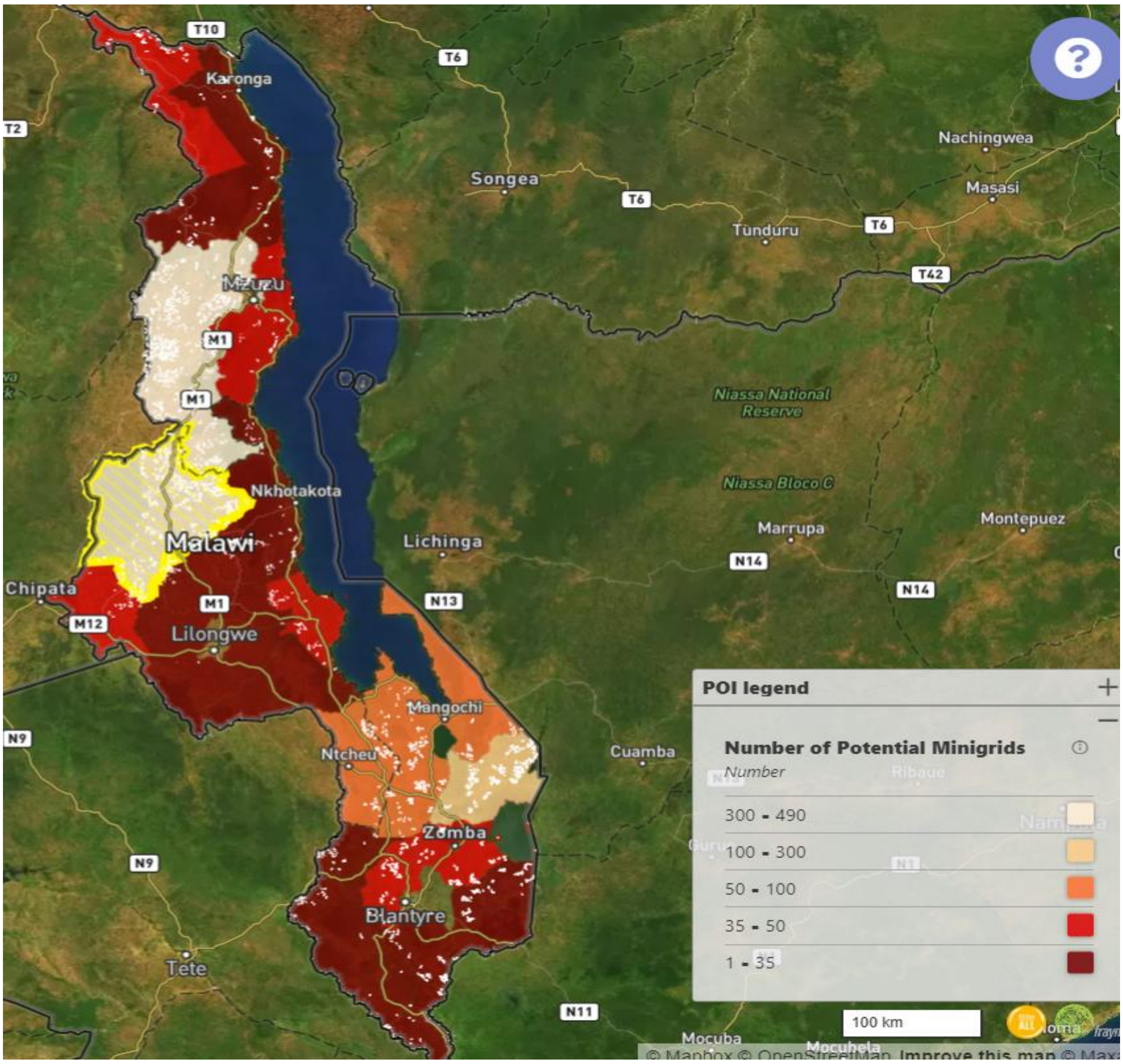

Figure 11: Spatial Distribution of Potential Minigrids in Malawi. Area With Yellow Boundary Is Kasungu District. Source [73]

3.1.1 Energy resources available in study Area.

The chosen area has potential for solar power generation, wind power and biomass. There is also potential of using diesel generator to produce electricity for the microgrid design. This section will describe the power sources that will be used for modelling the microgrid.

Solar Resources

There are generally good solar resources for Santhe area with Global Horizontal Irradiance (GHI) ranging from 4.960kWh/m^2/day to 6.670kWh/m^2/day with annual average irradiance of 5.60kWh/m^2/day. The solar resources are found to be lower between in June and July due to winter season in the area. The Figure 12 below shows the solar resources in the area.

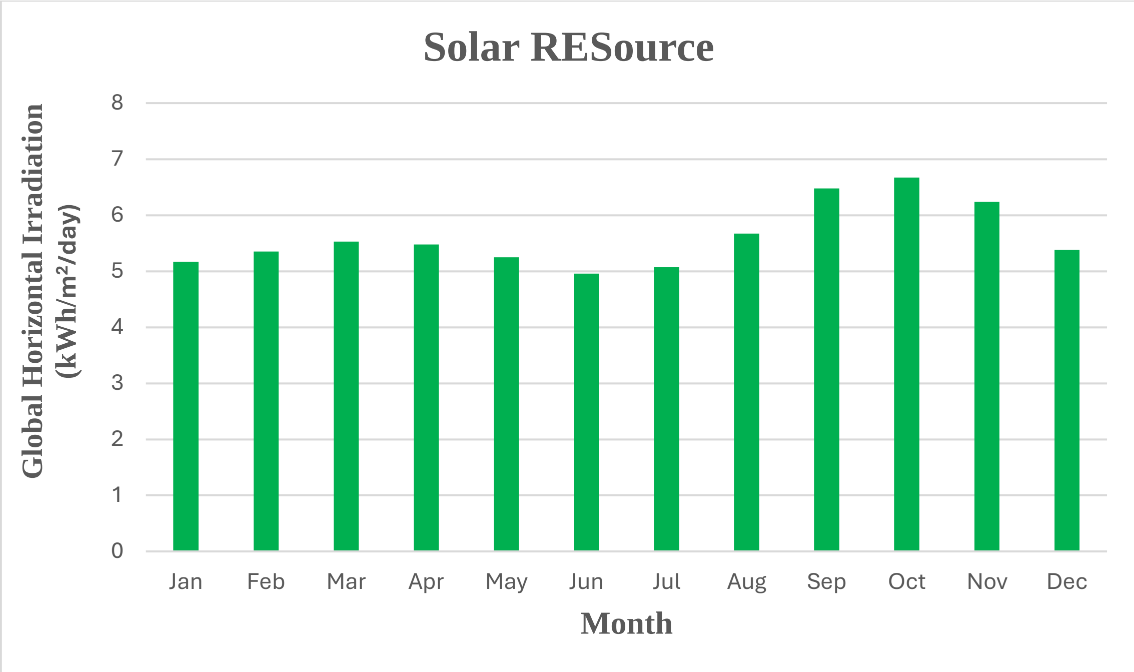

Figure 12: Annual Solar resources of Santhe Area in Kasungu district. Source HOMER climate data

Wind Resources

The Figure 13 shows considerable wind resources which may be favourable for small wind turbines for generating electricity to power the microgrid. According to the wind data provided by NASA the area experience wind speed of 4m/s to 7.6m/s with an annual average wind speed of 5.89m/s at a height of 10m and the speed would like increase at very high attitudes due less obstruction compared to the 10m height. The wind resources also follow season pattern like solar resources registering high speeds between July and November and peak speed in October.

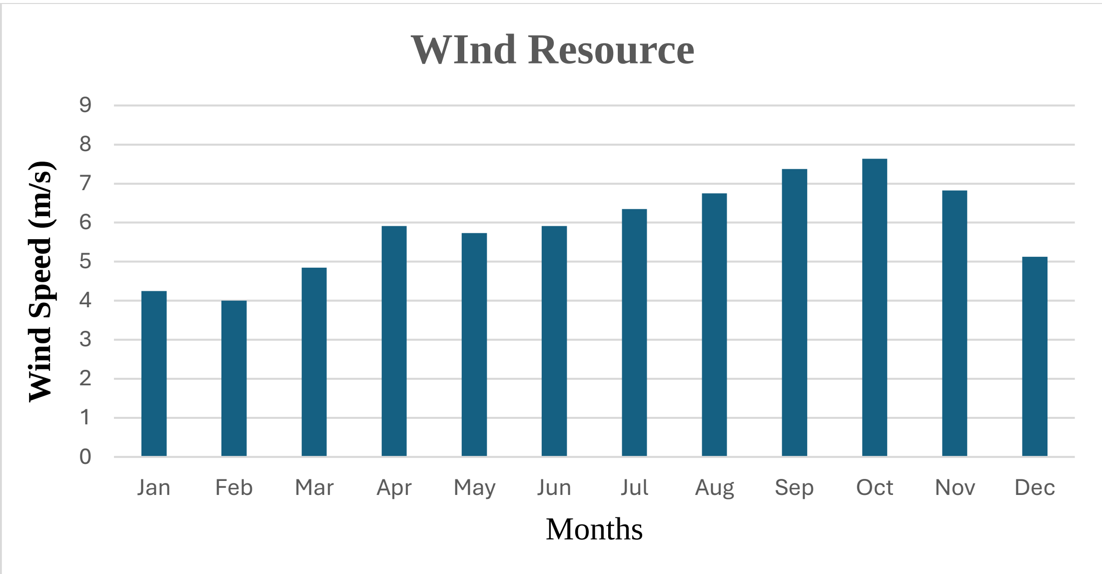

Figure 13: Santhe wind resources Source; HOMER climate resources

3.2 Object

The object of this study is to identify optimal combinations of power generation sources for hybrid systems that can enhance energy access and security in isolated communities in Malawi. Specifically evaluate various configurations of hybrid power systems combining renewable energy sources (such as solar and wind) with conventional generators and energy storage and determine the most suitable and cost-effective hybrid system designs that can reliably meet the electricity needs of remote Malawian communities.

3.3 Microgrid System Modelling

This section will discuss all components used in the modelling of the case study area to produce results for analysis of the study. The section discusses electrical demand modelling, PV modelling, wind modelling, battery storage system modelling and diesel generator modelling that will be used during simulation of results in HOMER Pro software.

3.3.1 Electrical demand modelling

HOMER Pro require electrical load profiles to simulate the correct results of the modelled system. As identified in the Malawi Integrated Energy Plan, this area is a potential site for microgrid installation, and it has no electrical connection. To model electrical demand is very challenging task as behaviour of electric load depends on the consumption of various devices that are switched on or off either automatically or like refrigerators and manually like TVs. Often electric demands profiles are modelled using constant electric impedance for simplicity but for more accuracy machine learning algorithms and or artificial neutral networks can be used [76].

This model considers basic household components like lights, radios, and electronic charging sockets for devices such as torches, phones, and rechargeable radios. Refrigerators, fans, and TVs were estimated for a specific number of households, as not all community members can afford these items. The model also includes a school with five building blocks, four printers, and a 1kW water pump for community domestic water supply. The Figure 14 illustrates the estimated daily profile demand for the system. The peak demand reaches 15.64kW, with high electrical demand between 16:00 and 20:00 hours when most components are functioning as people return home. Demand decreases from 21:00 to 04:00 hours as people sleep switch off most devices except for those with refrigerators and then begins to rise again as daily activities resume.

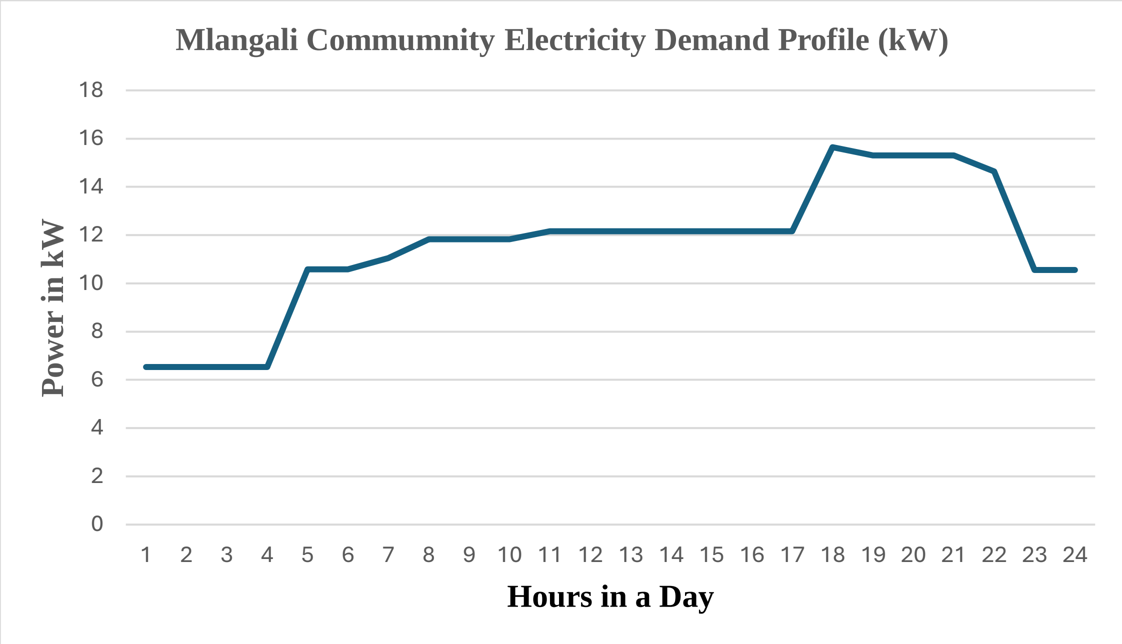

Figure 14: Estimated Daily Electrical Demand Profile

The main parameters from the modelled electrical demand can be seen from Table 2

Electrical Demand Main Values			
Annual Electrical Demand (MW)	Daily Mean electrical Output(kW)	Minimum Electrical Output (kW)	Peak Electrical Demand Output(kW)
100.8	11.51	6.53	15.64

Table 2: Electrical Demand Main Values

3.3.2 PV resources modelling

Photovoltaic systems convert energy from sun directly into electricity. The photovoltaic cells usually a strip of semiconductor material formed by crystalline silicon generates electricity when struck by the sunlight. Multiple cells can be assembled to modules that can be wired in multiple ways into arrays of any size and are considered cost effective systems for small off grid applications supplying power to homes and remote telecommunications [77].

The physical model of solar irradiance on tilted surface is given by the

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{1}$$

Where I_b and I_d are direct normal and diffuse solar radiations and R_d and R_r are tilt factors for the diffuse and reflected part of the solar radiation. I_T dependent on sun position which changes every month [78].

The hourly output power of PV system of the area covered by PV system $(A_{pv})m^2$ on average day of *j*th month when total solar radiation I_T (kWh/m^2) is incident of PV surface is given by:

$$P_{sj} = I_{Tj} \eta A_{pv} \tag{2}$$

Where η is the system efficiency given by:

$$\eta = \eta_m \eta_{pc} P_f \tag{3}$$

where η_m is the module reference efficiency, η_{pc} is the power conditioning efficiency and is the P_f packing factor. Module efficiency is also influenced by operating temperature which may affect power output. With known output power the PV is modelled as PV bus [77,78]. HOMER software uses solar resources which can be downloaded from NASA Climate Resources or other sources. For this modelling exercise NASA data from selected location and solar PV panels used will be outlined in input data section will be used for simulation purposes.

3.3.3 Wind resource modelling

Wind power resources has achieved a lot of success in past decades with high penetration rates. Though having wide acceptance wind power generation comes with challenges such as power generation fluctuations and difficult to predict with great precision which causes grid stability problems. In this model will look at wind power generation characteristics for wind turbine. Power output of wind turbine is dependent of height and speed characterisation factors [76,78]. The relationships are given by power -law equation.

$$V_z = V_i [\frac{Z}{Z_i}]^x \tag{4}$$

where V_z and V_i are wind speed at hub and reference height Z and Z_i, and x is the power law exponent.

The power output P_w from wind turbine generator can be calculated using the equation:

$$\boldsymbol{P_w} = \left\{\frac{P_r}{V_r{}^3 - V_{ci}}\right\} V^3 - \left\{\frac{V_{ci}}{V_r{}^3 - V_{ci}}\right\} P_r \qquad \mathbf{V_{ci}<V<V_r} \tag{5}$$

$P_w=0$ when $V<V_{ci}$, $P_w = P_r$ when $Vr<V<V_{co}$ and $P_w=0$ when $V>V_{co}$

Where Pr is rated power output, V_{ci}, V_{co}, and V_r are the cut-in, cut out and rated speed of the wind turbine. The Figure 15 below illustrates this model.
[78]

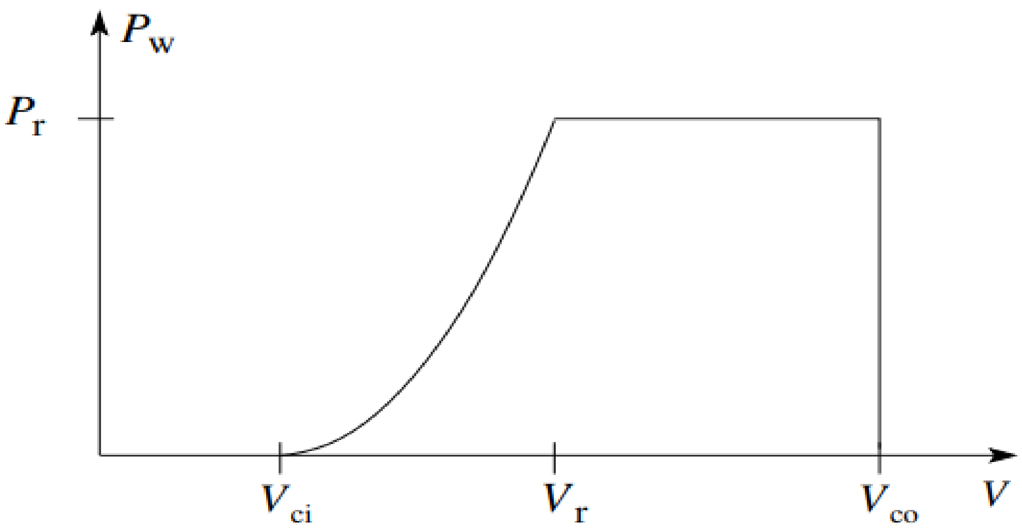

Figure 15: Power Output Profile of Wind Turbine. Source [78]

HOMER offers various types and characteristics of wind turbines which can be included in the microgrid simulation. The details for the wind turbine used for this study are outlined in then input section.

3.3.4 Battery storage modelling

Battery storage forms an integral part of microgrid networks. It works in times when demand is not met using supply or situations where there is blackout. Microgrids with high penetration of renewables uses battery storage to overcome challenges associated with intermittent supply or when the RES is not in function such as nighttime for solar and still day for wind generation systems. During superfluous power generation such as during daytime, solar PV may generate more power than what demand can use, excess power is stored in batteries to meet demands in times of less production or peak demand. Battery storage is used as complimentary to the microgrid and seized to meet demand needs during non-availability of RES [76]. The battery in this model is connected same bus as the PV and it has become the most common type of connecting the battery in most battery banks.

Battery capacity is measured in ampere-hours given by:

$$\boldsymbol{B_{rc}} = \frac{\boldsymbol{E_{C(Ah)} C(Ah) D_s}}{\boldsymbol{DOD_{max} \eta_t}} \qquad (6)$$

Where $E_{c\,(Ah)}$ is the load in ampere-hours, D_s is the autonomy or charge days, DOD_{max} is the battery maximum discharge depth and $\boldsymbol{\eta_t}$ is the temperature correction factor and the charge quantity of the battery bank is calculated by [76]:

$$\boldsymbol{E_B(t) = E_B(t-1)(1-\sigma) + \left(E_{GA}(t) - \frac{E_L(t)}{\eta_{inv}}\right)\eta_{battery}} \quad \textbf{(7)}$$

Where $E_B(t)$ and $E_B(t\text{-}1)$ are the charge quantities of the battery bank at time *t* and *(t-1)*, $\boldsymbol{\sigma}$ is the hourly self-discharge rate, $E_{GA}(t)$ is the total energy generated by the total renewable energy source after energy loss in the controller, $E_L(t)$ is the load demand at time *t* and η_{inv} and $\eta_{battery}$ are efficiency of the inverter and the charge efficiency of the battery bank [78].

HOMER allows simulations battery storage and has been used in this modelling for the purposes of meeting demand when renewable generation is not available, and its details are outlined in the inputs section.

3.3.5 Diesel generator modelling

The selected area for modelling the microgrid is not connected to any power grid and it is far from main power grid connection which makes this microgrid operating in islanding mode and if the load requirements are not mate by RES or battery storage, the load demand must be supplied by the generator. Diesel generators are modelled as dispatchable unit that can supply energy in critical times and in absence of high demand the diesel generators can also be used for charging battery bank depend on the type of dispatch strategy used [76,78].

3.4 Scenarios Development

This section will discuss the scenarios modelled for this study. It is important to note that the system operates in islanding mode, functioning as a standalone microgrid without connection to the main grid. The model will be simulated using software across four distinct scenarios. These scenarios are designed to evaluate various configurations and operational strategies of the microgrid, likely considering different combinations of renewable energy sources, storage systems, and backup generation. The specific details of each scenario will be explored in the subsequent sections, providing insights into the performance, reliability, and economic viability of different microgrid configurations under islanded conditions.

- Scenario 1 Solar PV – Battery storage which is also called business as usual model.
- Scenario 2 Solar PV-Diesel Generator -Battery Storage
- Scenario 3 Solar PV – Wind Turbine – Battery Storage
- Scenario 4 Solar PV- Wind turbines- Diesel Generator -Battery Storage

3.4.1 Solar PV – battery storage

This Scenario is also called "business as usual" scenario because most Hybrid Energy Systems are based on solar PV and its complimentary battery storage. In this scenario HOMER will use the inputs for the solar PV, energy converter and battery storage to simulate system. the system works in a way that when solar PV generate more electricity it will be used to charge batteries to be used when solar PV is not available or inadequate to meet the load demand especially at nights when solar radiation is non-existent. The sizing of PVs, the converter and battery Bank were optimised by HOMER to give us the best choice with minimum capital cost but enough power to cover the demand.

3.4.2 Solar PV-diesel generator -battery storage

In this scenario, a hybrid microgrid system operating in islanding mode is simulated, comprising solar photovoltaic (PV) panels, a 21kW diesel generator, and battery storage. The number of solar PVs and the capacity of the energy converter are optimised using HOMER (Hybrid Optimization Model for Electric Renewables) software. The system's operational strategy prioritizes solar PV generation to meet the primary load demand, with excess electricity used to charge the battery bank. When solar production and battery storage are insufficient to meet demand, the diesel generator serves as a dispatchable unit, providing power to the microgrid. This configuration aims to maximize renewable energy utilisation while ensuring reliable power supply through a combination of energy storage and backup generation, making it suitable for remote or off-grid applications where grid connection is not feasible or dependable.

3.4.3 Solar PV – wind turbine – battery storage

In this scenario the solar PVs, energy converter will be simulated together with wind turbines and the battery storage in islanding mode. The system uses both wind and solar simultaneously to meet load demands of the microgrid with access generation used to charge the battery storage. In times of insufficient renewable generation, the battery storage act as buffer system to meet the load demand. The size of PV array and converter will be optimised by the HOMER to obtain economical configuration of the system. The details of all components used are provided in input section including turbine details.

3.4.4 Solar PV- wind turbines- diesel generator -battery storage

In this scenario, comprehensive hybrid energy System integrating solar PV, wind turbines, diesel generator and battery storage will be simulated in HOMER. The system prioritizes renewable generation and storage, with diesel generator serving as dispatchable unit. Renewable resources (wind and solar) are used as primary power sources, with excess generation charging the battery bank. When there is insufficient renewable generation and battery storage the diesel generator activates supplying power to the microgrid and charging the batteries. This scenario maximises the use of RES ensuring system reliability through diversified generation sources and energy storage.

3.5 HOMER Input Parameters

Mlangali village currently lacks power source, making this study the first of its kind in the area. To estimate input prices for HOMER simulations, reference is made to two existing off-grid systems in Malawi implemented by Energy Access through Social Enterprise (EASE) and United Purpose. The Mthembanji microgrid in Dedza district features a 12kW solar PV array with 19kWh battery storage, serving 60 connections at an estimated capital expenditure of $102,000. The Kudembe microgrid in Balaka district uses a 11kW solar PV array with 20kWh storage capacity, connecting 50 households at an estimated capital expenditure of $108,500 [74]. These functional microgrids will serve as benchmarks for estimating input prices in our HOMER simulations for Mlangali village.

HOMER requires input data to perform simulations and give out outputs which will help determine if the designed system has achieved the goals of the study. The Figure 16 below summarises some of the input data information in HOMER and expected outputs.

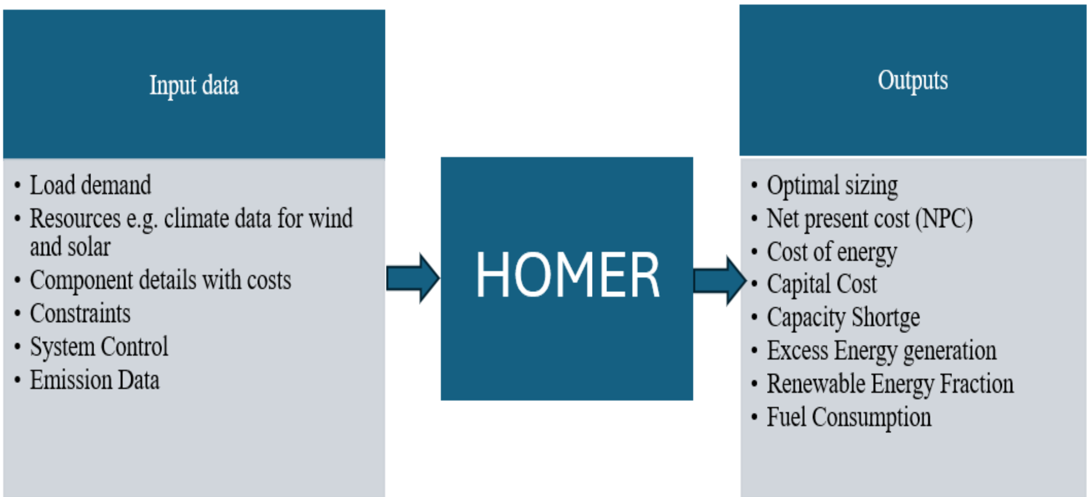

Figure 16: Representation of inputs and Outputs for HOMER. Source [79]

The following are input parameters that will be discussed in this section.

3.5.1 Electricity demand

The electricity demand load for this project was modelled based on assumptions of the electrical components that are likely to be used by the households include in the community to be serviced by the microgrid. The model is based on 60 households, 10 businesses shops, five blocks of primary school and water pump to supply water to the community. The typical daily modelled demand and main electrical demand values are listed in Table 3 below and Table 2 in section 3.3.1.

Hours	Load Demand (kW)
0	6.533
1	6.533
2	6.533
3	6.533
4	10.579
5	10.579
6	11.048

7	11.826
8	11.826
9	11.826
10	12.161
11	12.161
12	12.161
13	12.161
14	12.161
15	12.161
16	12.161
17	15.645
18	15.31
19	15.31
20	15.31
21	14.64
22	10.553
23	10.553

Table 3: Daily Electrical Demand of the Modelled Community

3.5.2 Solar PVs specifications

The solar PV modelling, Canadian Maxpower (CS6U-340M) flat plate PV manufactured by Canadian Solar with operating temperature of 45^{0}C and 0.41 temperature coefficient has been selected from HOMER library with lifetime of 25 years. The details for initial capital cost and replacement cost plus other important details are listed in the Table 4 below. These costs have been set based on the existing microgrid in Malawi and current costs [80]. Unlike other technologies such as wind and generators the PV plates can be locally supplied. HOMER will use the details to simulate and optimise the total capital expenditure on each scenario.

Specification	Value
Type	CS6U-340M PV plate
Capacity (kW/panel)	0.34kW
Capital cost ($/kW)	3235/2kW
Replacement Cost ($)	1600

O&M costs ($/year)	320
Pannel Efficiency (%)	17.5
Lifetime	25

Table 4: HOMER Input Parameters for Solar PVs Source [80]

3.5.3 Wind turbine specifications

In the study on wind turbine costs for the HOMER microgrid design in Malawi, an AC type wind turbine (model MT-10kW manufactured by PVMARS) with a hub height of 50 meters was considered with 20 years life span. The study proposed capital cost for the wind turbine at $4000 per kW, which includes estimates of shipping costs. Additionally, the replacement cost is $3200 per kW (representing 60% of the capital cost), and the annual operations and maintenance cost is $500 per unit [81]. The Table 5 below summarise total specifications.

Specification	Value
Type	MT-10kW
Capacity (kW)	10
Capital Cost ($)	40000
Replacement Cost ($)	32000
O&M ($/year)	500
Hub Height (m)	50
Lifetime (years)	20

Table 5: HOMER Input Parameters for Wind Turbine. Source [81]

3.5.4 Diesel generator

Factoring in the peak load demand of the chosen community and potential load growth the diesel generator was selected to be generic medium generator in HOMER and set to 21kW capacity. The costs for this generator have been set with reference made to previous study caried in 2021 in Malawi [81] which estimated that the capital cost and replacement cost was $400 per kW with an operation and maintenance $0.02 per operating hour [82]. The Table 6 below has details of the generator.

Specification	Value
Type	Generic Medium Generator
Capacity (kW)	21
Capital Cost ($)	8400
Replacement Cost ($)	8400
O&M ($/h)	0.02
Efficiency (%)	30
Lifetime (hours)	30000
Fuel Price($/L)	1.6

Table 6: HOMER Inputs for Diesel Generator. Source [81]

3.5.5 Battery storage

The selected battery storage type for this system is the L-51220C Lithium Ion Battery manufactured by Revov in south Africa [83]. Due to intermittent power supply of renewables the Li-ion Battery act as buffer when the load demand is not met by the existing renewables and is recharged when the system generate more electricity than the load demand can consume. The capital cost and replacement cost are set to same value at $4,500.00 [80,84]. Operation and maintenance costs are set at $300 in every five years which translates to $60/year for each Li-ion battery for residential and medium scale applications and it should also be noted that as the world is moving towards carbon net zero the prices of renewables are decreasing so as storage batteries [85]. The details for the battery storage are given the Table 7 below.

Specification	Value
Type	L-51220C Li-ion Battery
Capacity (kWh)	11.26
Capital Cost ($)	4500
Replacement Cost ($)	4500
O&M ($/year)	60
Round Trip Efficiency (%)	95
Lifetime (years)	15

Table 7: HOMER Input Parameters for Li-ion Battery Storage. Source [80]

3.5.6 Converter

Converter, also known as inverter, is the device that convert direct current (DC) to alternating current (AC) or the other way round depending on the system configuration. Most load demand uses alternating current it is only fair to supply the power in AC for to avoid damaging their devices. The solar panels and battery storage in hybrid systems produce power in DC which must be converted to AC before supplying to consumers. The selected invertor in this modelling is 15kW 48V 3-phase Blue Mountain hybrid inverter. The capital and replacement cost are the same while operations and maintenance costs are set at $300/kW in every five years [85]. The **Table** 8 below gives details of the inverter.

Specification	Value
Type	Blue mountain
Capacity (kW)	15kW
Capital Cost ($)	3500
Replacement Cost ($)	3500
O&M ($/year)	60
Round Trip Efficiency (%)	91
Lifetime (years)	15

Table 8: HOMER Inputs for Converter. Source [85]

3.5.7 Other Costs

HOMER provides the option to incorporate the system's fixed operation and maintenance (O&M) costs, which represent the recurring annual expenses that arise irrespective of the power system's size or configuration. These costs encompass those associated with operating the system, routine maintenance, and equipment upkeep. For this microgrid design, the fixed system cost and the O&M costs have each been set at $800 per year. The inclusion of these fixed system and O&M costs may influence the overall capital cost and net present cost of the microgrid system, which in turn could affect the levelised cost of energy. However, it is important to note that these costs do not have any bearing on the rankings of different system configurations. This is because the fixed costs are applied uniformly across all potential system designs, thus maintaining the relative economic performance of each option when compared to others [86].

3.6 Software Adopted and Validation.

During first screening of software available to model microgrids and hybrid energy systems the following software were examined for purposes of comparison [87,88] HOMER Pro (Hybrid Optimization Model for Energy Resources) which is used for modelling and optimising microgrid designs, RET-screen developed to assist in the preliminary assessment of potential renewable energy projects [89], PVSyst for detailed Photovoltaics system design and analysis [88] and MATLAB which is used for advanced data analysis, modelling and simulations various systems including renewables [90]. After the assessment of these modelling tools HOMER Pro was selected to be the most suitable for this project.

- **Software Description** [86]

HOMER Pro is user friendly software with great graphic interface, and it already has needed elements for this project. HOMER allows quick optimisation calculations, and it is considered as the best hourly simulation and analysis tool for hybrid renewable electric generation systems in the world for both grid connected and off grid microgrid systems.

HOMER requires inputs to simulate and give results. The inputs that HOMER requires to simulate include electrical load profiles which shows electricity demand over time, resources data which include solar irradiance for photovoltaic simulation, wind speed for wind turbines simulation and these resources data are specifically tailored to the location of project. Other inputs include components parameters such details about generators, inverters, batteries and economic parameters such as costs, discounts rates and inflation rates.

HOMER simulation algorithm is implemented in three stages namely simulation, optimisation and sensitivity analysis.

1. **Simulation:** HOMER simulates the system by making energy balance calculations in each time step for the whole year by comparing electrical load demand and the energy system supply available.

2. **Optimisation:** During this stage HOMER examine all possible combinations of the system and then sorts the system based on optimisation variables such as costs and reliability.

3. **Sensitivity analysis**: HOMER explores thousands of possibilities to assess the impact of the variables beyond human control such as windspeed, solar irradiation on the designed system.

3.6.1 HOMER Modelling Variables

HOMER focuses on producing a system with lowest net present cost, levelised cost of energy and system with highest renewable fraction depending on the system constraints. The following are some of economic variables that HOMER uses when calculating the system results.

NET Present Cost (NPC) – it is defined as the sum of all discounted cash flows for each year of the project life span. The costs include capital costs, replacement costs, Operations and Maintenance costs during the project life span [91]. It can also be calculated the formula below

$$C_{NPC} = \frac{\textbf{Total annualised costs of overall System}}{\boldsymbol{CRF}(\boldsymbol{i},\ \text{Rproject})} \tag{8}$$

Where $R_{project}$ is project life span for this study is 25 years, CRF is capital recovery factor, and I is annual discount rate for this project is set at 5%.

Levelised cost of Energy (LCOE) is defined as the average cost of electric energy generated per kWh. It is found by dividing annualised cost of the system by total electricity served [92,93].

$$\text{LCOE} = \frac{Total\ annualised\ Cost\ of\ \ system(\frac{\$}{year})}{Totat\ Electricty\ Load\ served\ (\frac{kWh}{year})} \tag{9}$$

Renewable Fraction is defined as the fraction of energy delivered to the load that was produced by renewable energy sources [93]. It is calculated using the formular below:

$$\text{Renewable Fraction (\%)} = 1 - \frac{Non\ renewable\ production\ (\frac{kWh}{year})}{Total\ elctric\ Load\ Served\ (\frac{kWh}{year})} \tag{10}$$

Carbon Dioxide (CO_2) Emissions

To calculate $\mathbf{CO_2}$ emissions HOMER by taking the product of emissions factor (Kg of $\mathbf{CO_2}$ emitted per unit fuel consumed) by the total annual fuel consumption. It is given by the formula below [93]:

$$\%\ CO_2\ \text{Emission decreased} = \frac{CO2\ emission\ of\ hybrid\ combination\ (\frac{kg}{year})}{CO2\ emission\ of\ base\ model\ (\frac{kg}{year})} \text{....(11)}$$

3.6.2 HOMER Limitations

To get the best results out of any software program to be used in a project it is essential to understand its constraints and limitations. HOMER just like any other software has its limitations. The flowing are limitations according to comprehensive review of hybrid energy system done by Sunanda Sinha, in his paper, "Review of software tools for hybrid renewable energy systems" [94].

1. HOMER operate on main single objective reduction of net present cos through reduction of system costs such as operations and maintenance costs. Although other objectives such as system configuration, performance analysis, and environmental impact analysis are considered but the core is minimising costs which may lead the Software to disregard other issues that may arise.
2. HOMER does not include intra hour variability rather it averages out hourly energy production which may smooth out short-term fluctuations which may be of important use in making precise predictions in hybrid energy system.

3.7 Optimisation and Modelling Results

The best configuration and component sizes to meet the electrical demand requirements at the lowest possible cost are found using HOMER sizing tool [95]. The software used inputs defined by solar resources, wind resources, and hybrid system components such as

PV panels, wind turbine, diesel generator, battery converter and the electrical demand of the community, described in section 3.5 to determine the number of each component required to meet the demand. The simulations were performed for 8760 hours of the year and the main economic outputs based on capital cost, net present value and levelized cost of energy were obtain for each scenario modelled.

3.7 System constraints and Power Dispatch Strategy

The operating life span of the project was set to 25 years. To ensure reliable simulations, the maximum unserved load constraint was set to 0% to obtain only systems that are capable of meeting 100% of the community load demand [81]. As for discount rate and inflation in HOMER Pro are set at 5% and 2% respectively.

The dispatch strategy in hybrid energy systems is a set of rules governing the operation of diesel generators and other components [95,96]. HOMER has two dispatch strategies: load following and cycle charging [97]. In the load following strategy, diesel generators operate solely to meet the primary load demand, without charging batteries [96]. This reduces generator runtime but may lead to increased battery wear. On other hand, the cycle charging strategy allows diesel generators to charge batteries in addition to meeting the load demand [97] This can Result in longer generator runtimes but potentially reduces battery wear.

A more advanced approach is the combined dispatch strategy, which dynamically switches between load following and cycle charging based on system conditions and energy requirements [97] This adaptive method aims to optimise generator usage and battery life while minimising operational costs. HOMER simulations use dispatch strategies to find the most economically efficient use of diesel generators within the system [98]. It considers factors such as fuel consumption, generator efficiency, battery state of charge, and renewable energy availability to find the optimal dispatch strategy for a given hybrid energy system configuration.

The choice of a dispatch strategy significantly impacts system performance, fuel consumption, and overall levelized cost of energy (LCOE) [96]. Therefore, careful consideration of dispatch strategies is essential in the design and optimization of hybrid energy systems, particularly those incorporating diesel generators and battery storage.

For this simulation model, the load following dispatch strategy has been considered to maximise the benefits of systems which incorporate both battery storage and generator.

3.9 Costs and Emissions

The costs incurred in the scenario simulations do not include the transmission of electricity to individual user homes. Essentially, homeowners are responsible for the expenses associated with the transmission cable from the distribution centre, which is typically a few meters away. If homeowners are unable to manage these costs, they have the option to purchase the cable on loan from the power supplier. The loan can then be repaid through deductions from their monthly electricity unit purchases. For this system, it is assumed that the power generation system will be constructed at the centre of the community, with the transmission from the generation plant to four distribution sections of the community funded by the supplier. However, for individual homes, homeowners must consult the supplier for details on the type of materials required or opt to purchase these materials directly from the power supplier.

Again, this designed to have standalone power station with office which will include area for PV and all necessary components. The most preferred infrastructure type is using shipping containers which may be remodelled into office and storage for batteries and other electrical connections.

Additionally, the emissions discussed in these results account solely for those directly from power generation, specifically from the diesel generator supplying power to the community. Emissions from transportation and other sources of carbon monoxide (CO), carbon dioxide (CO_2), or sulphur compounds are not included in these calculations

4.0 RESULTS AND DISCUSSION

This section includes scenario simulation results, discussion and analysis.

4.1 Scenario results and discussions

4.1.1 Scenario 1: Solar PV – Battery Storage

This scenario employs a 100% renewable energy system to supply electricity to the community, and it is the most common hybrid energy configuration in sub-Saharan Africa due to year-round solar availability. Both PV panels and battery storage are connected to a DC bus, while the load is connected to an AC bus, with power converted from DC to AC via a converter to meet demand. The schematic arrangement of all components used in the scenario simulation is illustrated in the Figure **17** below.

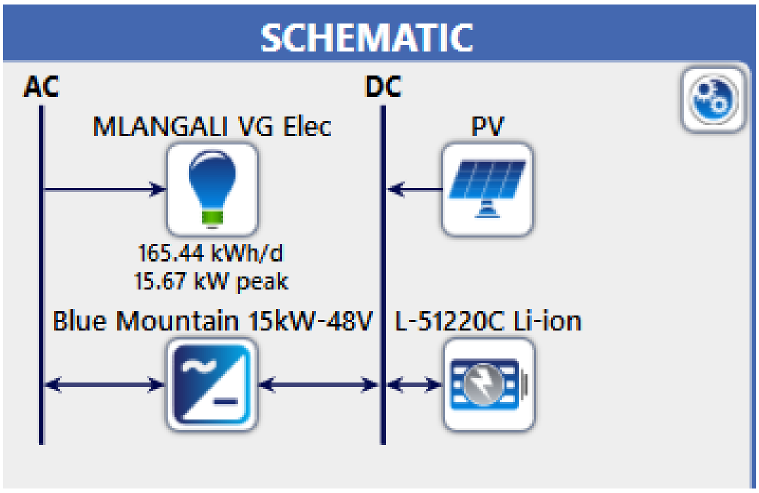

Figure 17: The Schematic of Scenario 1

Scenario 1 System Performance Results

For all scenarios simulation, the constraints were set as follows: discount rate at 5%, inflation at 2%, project lifetime at 25 years, and both system fixed costs and O&M costs at $800. The HOMER optimisation process, using these constraints and component input parameters, produced the following results in Table 9 and Table 10 for the system:

Characteristic	Value
Renewable Fraction (%)	100
LCOE ($/kWh)	0.123
CO_2 Emissions (kg/year)	0
Net Present Cost ($)	131,000.00
Initial Capital Cost ($)	64,000.00
Unmet load (%/year)	0.03
Excess Electricity (%/Year)	7.33
Total power generated (MWh/year)	21.2MWh

Table 9: Scenario 1 Main results

In this scenario, HOMER optimisation initially recommended an 18kW converter. However, to ensure safe operation and accommodate potential unexpected changes in load demand, two 15kW converters were manually selected using HOMER's search space function. This approach allows for component selection without relying on optimisation for that specific element. While HOMER optimised all other components, the converters were manually specified across all scenarios in this study.

Component	Quantity	Rated(kW)	Power Generated
CS6U-340M PVs(0.340kW)	36	12.1	21.2MWh/year
Converters (15kW)	2	30	_
Li-ion Batteries(11.6kWh)	8	90Kwh	_

Table 10: Scenario 1 Components Quantities

Total Power Generation

The simulation results give 12.1kW PV system, generating 21,209kWh (21.2MWh) annually, which translates to a significant 35.1% PV penetration and a 20% capacity factor, running for 4,402 hours per year. To ensure continuous power supply during nighttime or periods of insufficient PV generation, the system incorporates eight 11.26kWh Li-ion batteries a total of 90kWh battery storage, providing energy storage solution.

This battery configuration shows remarkable resilience, capable of powering the simulated load for 10.5 hours without relying on external utility sources. The system's efficiency is further highlighted by its ability to meet all load demands throughout the year without any power shortages generating a 7.33% excess power, proving its reliability and potential for future expansion or energy export.

The Figure 18 below shows the monthly power generation throughout the year, with September and October being the peak months and February experiencing the least generation.

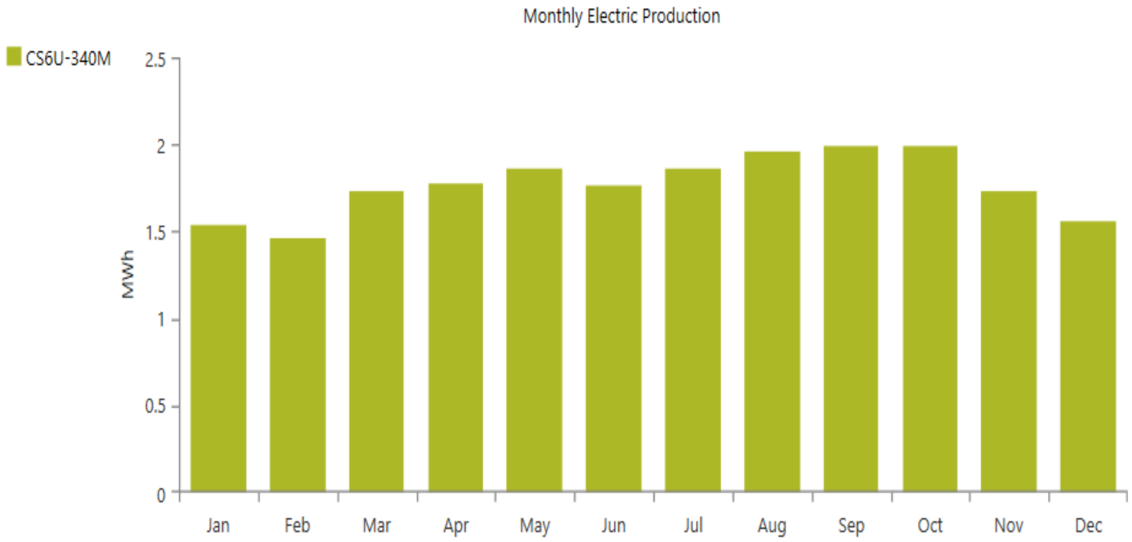

Figure 18: Monthly Electricity Production

From the **Figure** 18 above power production is very high between months of August to October reaching almost 2MWh for each month, this is because during these months it's when the area receives highest solar radiation. Months between November to February power production averaged at 1.5MWh which is low compared to other months because of these months experience cloudy rain skies which reduces solar radiation hence low production of electricity.

Power Output and Electrical Demand Balance

The Figure 19 below displays the results from a week in October, demonstrating how the system balances power output and load demand. The plotted graph shows that the system can adapt to changes in demand and generation sources, ensuring uninterrupted power supply to the community. It is evident that BESS and PV generation complement each other; when PV output is insufficient, especially at night when there is no solar radiation, BESS discharges power to meet demand. Conversely, when PV generation is in excess, it charges the batteries.

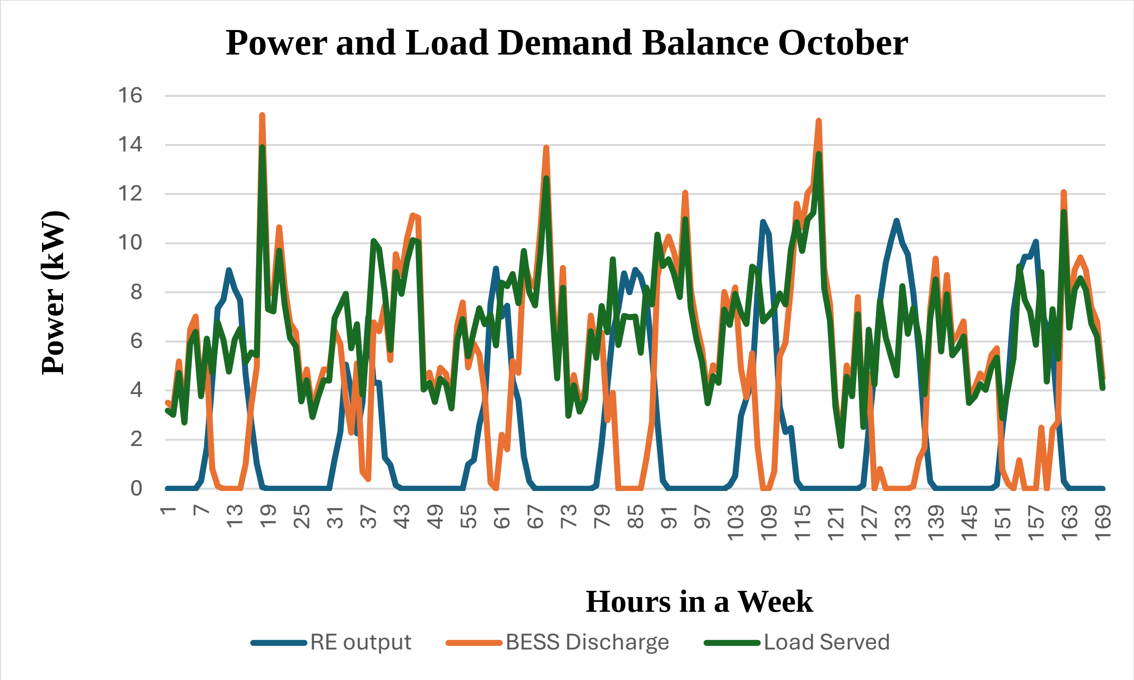

Figure 19: Power and Load Demand Balance October

The Figure 20 shows the results from month of February which experience low PV generation also demonstrating the system ability to respond to demand and generation changes.

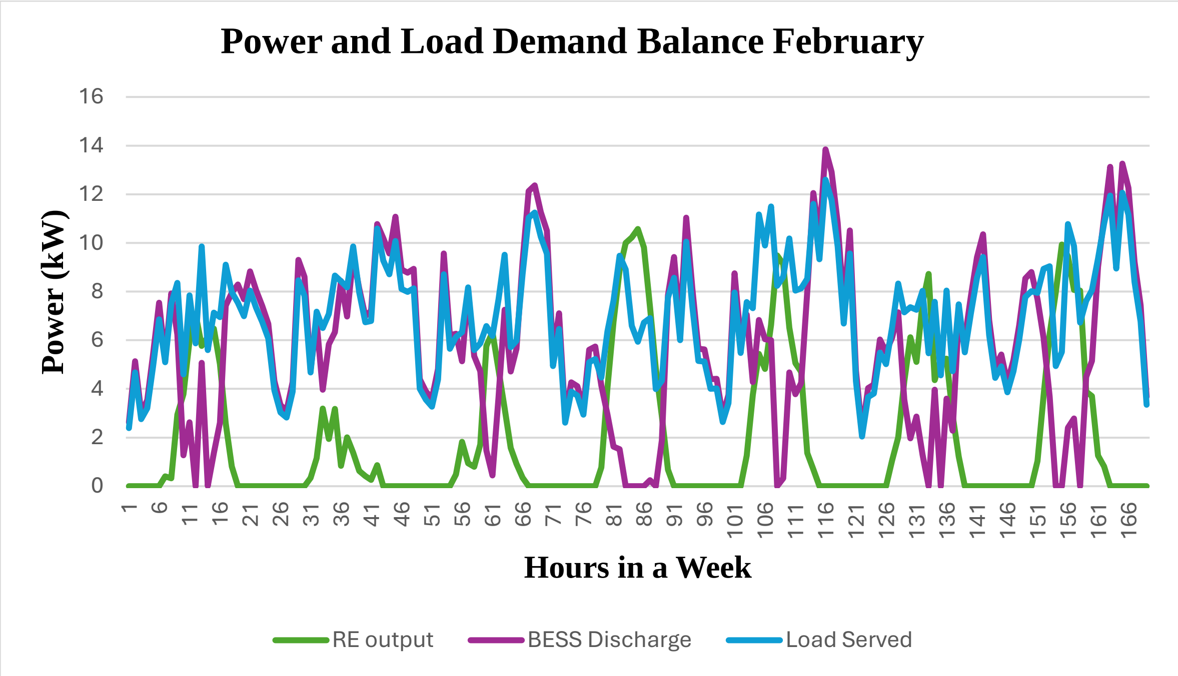

Figure 20: Power and Load Demand Balance February

Power generation and Battery State of Charge

The Figure 21 illustrates the scenario performance between power generated and BESS state of charge during a week in October, when PV output is at its maximum. On six out of the seven days, the battery was charged to full capacity, indicating that the PVs generated sufficient power to meet both the load demand and the BESS requirements. This suggests that during this period, a substantial amount of excess energy was generated.

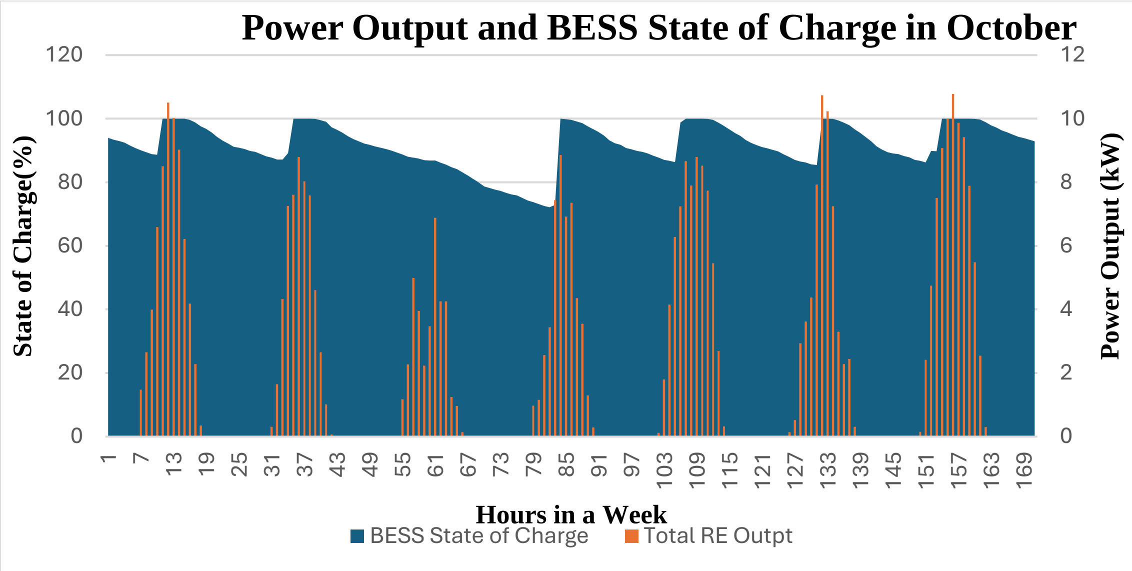

Figure 21: Power Output and BESS State of Charge

From the Figure 22, it is evident that in February, the battery state of charge frequently fell short of full capacity. This was due to low PV generation, likely caused by the rainy season in the region, which is characterised by cloudy skies. The plotted graph shows that out of seven days in the week, the battery only reached full charge on three days.

The graphs indicate that the batteries are not being fully utilised, even though they are set to a minimum Depth of Discharge (DoD) of 20%. Most of the time, the battery levels remain above 80%, even after nighttime, as shown in both Figure 21 and Figure 22 and in subsequent section results about BESS state of charge. This could mean that HOMER optimiser recommended too many batteries for the system, and fewer batteries might have been sufficient. Alternatively, it might suggest that HOMER has limitation when it comes to optimising the exact number of batteries needed for the system.

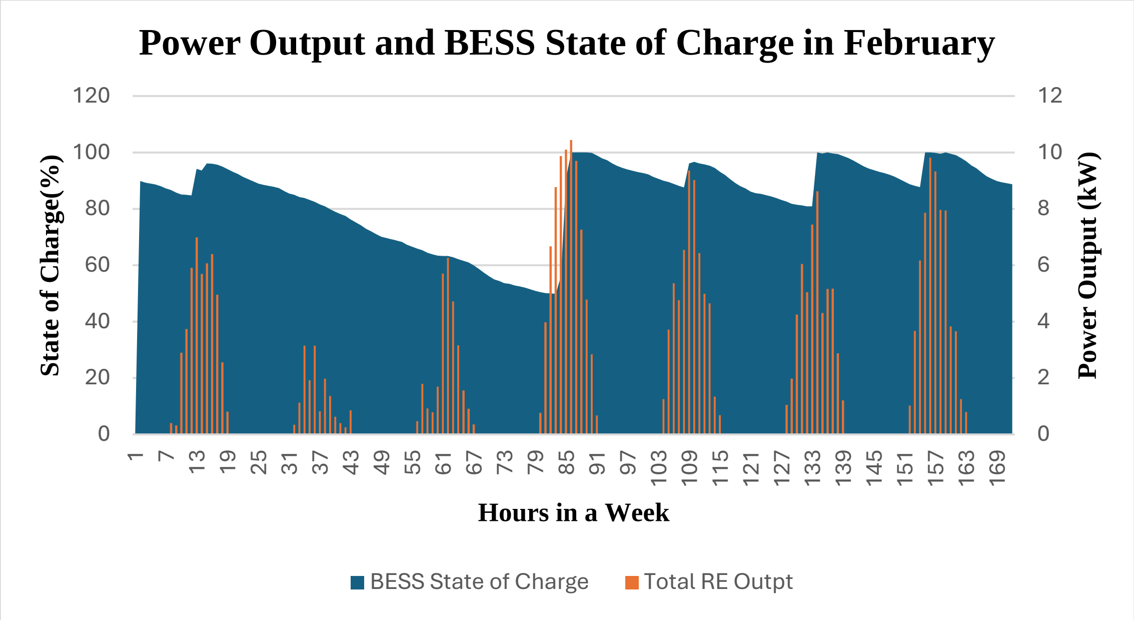

Figure 22: Power Output and BESS State of Charge February

Scenario 1 Costs results

The optimisation of HOMER components for a PV-Li-ion storage system yielded a cost-effective configuration with notable results. The optimized system achieved a significant capital expenditure calculated at $64,000.00 that is the capital required to have the system running with Net present value of $131,000.00 and the levelised cost of energy (LCOE) was calculated at $0.123/kWh for the whole period of 25 years, which is substantially lower than the current cost of electricity from minigrids and independent solar users in Malawi, estimated at around $0.45/kWh [10]. This optimisation shows the potential for renewable energy systems to provide more affordable and environmentally friendly power solutions and improving power access in addition to existing alternatives in the region.

The Table 11 shows system components costs required for each component in the system.

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
System Converter	$7,000.00	$3,920.27	$2,103.34	-$2,543.50	$10,480.11
CS6U-340M PV	$19,578.49	$0.00	$33,945.63	$0.00	$53,524.12
Li-ion Battery	$36,000.00	$20,161.37	$8,413.36	-$13,080.84	$51,493.89
Other	$800.00	$0.00	$14,022.27	$0.00	$14,822.27
System	$63,378.49	$24,081.63	$58,484.59	-$15,624.33	$130,320.38

Table 11: Scenario 1 System Components Costs

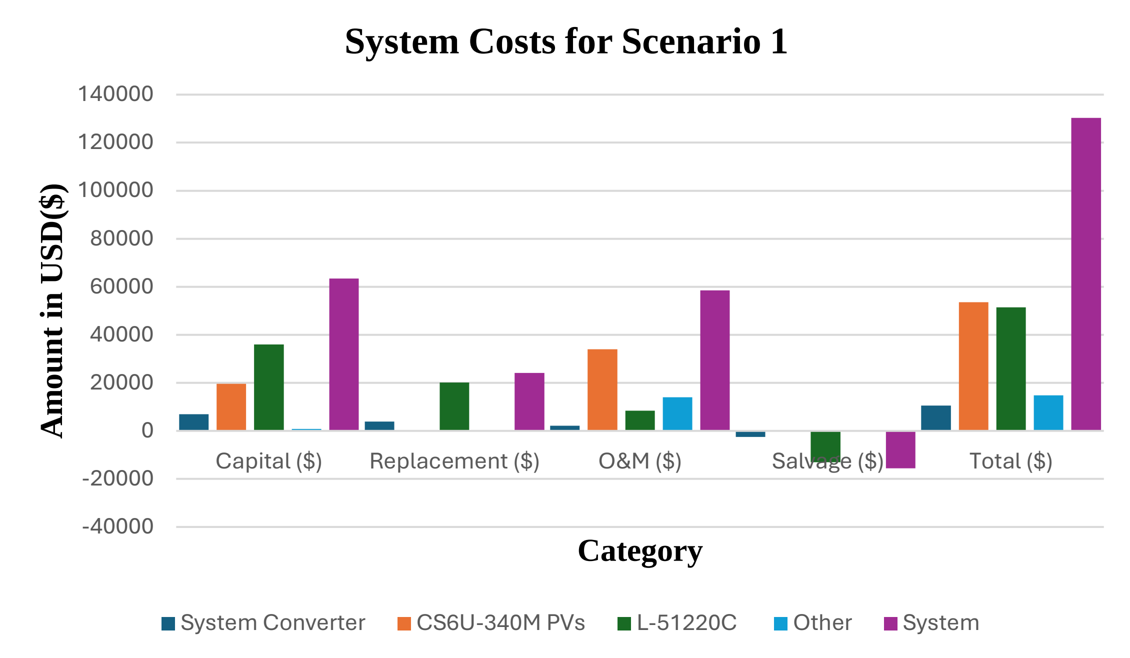

Figure 23: Scenario 1 System Costs

From the Table 11 and Figure 23, it is observed that lithium-ion batteries have the highest capital expenditure and replacement costs. This is due to the system's reliance on a single generation source, necessitating substantial storage capacity, and the batteries' 15-year lifespan, requiring replacement before the project life span. PVs dominate the O&M costs as they need regular cleaning to maintain efficiency, especially during the dry, windy, and dusty season of the region.

Energy Security

This scenario has one generation and backup battery storage which makes it secure, but presence of single generation source makes it vulnerable as failure of solar PVs or prolonged severe cloudy weather may result in poor electricity generation and poor battery charging which may result in the whole microgrid being offline when BESS is depleted. Therefore, it can be concluded to have low security.

Emissions

This system has 100 percent renewable fraction which means zero Greenhouse gas emissions, that is no emission of CO_2, CO, Sulphur and Other dangerous gasses.

4.1.2 Scenario 2: Solar PV-Diesel Generator -Battery Storage

This scenario integrates both renewable (Solar PVs) and dispatchable non-renewable (21kW diesel generator) generation sources, along with battery storage. The simulation employed load following which allow generators to supply electricity to the load to reduce run time. HOMER optimises this system to achieve the most economical use of the generator, reducing run time and operational costs, thereby lowering the Levelized Cost of Energy (LCOE) to obtain the most affordable configuration.

Figure 24 is the system schematic comprising of a diesel generator connected to the AC bus, while PVs and battery storage are connected to the DC bus. These components are linked by a system converter that facilitates power conversion between AC and DC, enabling the DC components to supply electricity to the AC load demand.

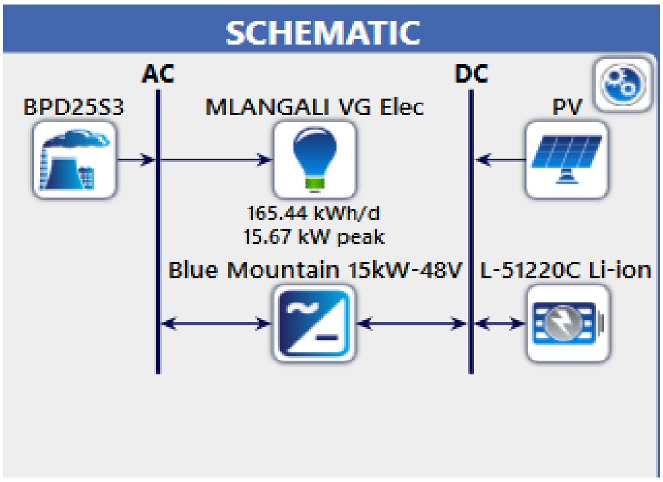

Figure 24: The Schematic of Scenario 2

Scenario 2 System Performance Results

The simulation of a combined PV-Battery Energy Storage System with a Diesel generator in Scenario 2 achieved power generation of 21MWh, a high renewable fraction of 97.3% and minimal excess energy of 4.66%, while maintaining 0% unmet electric load. These results highlight the system's efficiency in energy utilisation.

The **Table** 12 below has details of important results from the Scenario system Simulation.

Characteristic	Value
Renewable Fraction (%)	97.3
LCOE ($/kWh)	0.103
CO_2 Emissions (kg/year)	973
Net Present Cost ($)	110,000.00
Initial Capital Cost ($)	48,000.00

Excess Electricity (%/Year)	4.66
Unmet Electrical Load (%)	0
Total power generated (MWh/year)	21MWh

Table 12: Scenario 2 Main results

Initial optimisation results for this system rated the system converter at 14.1kW but for system safety and room for expansion two converters rated 15kWh each have been used in the search space function for this scenario while optimising all components. The components quantities and their individual and system rating are in **Table 13** below.

Component	Quantity	Rating (kW)	Total power generated
CS6U-340M PVs(0.340kW)	33	11.1	19.4Mwh/per year
Diesel Generator(21kW)	1	21	1.6MWh/year
Converters (15kW)	2	30	_
Li-ion Batteries(11.6kWh)	3	34	_

Table 13: System Components Quantities

Total Power Generated

The two generation sources, Diesel Generator (DG) and Photovoltaic (PV) system, produced a total of 21MWh/year. The PV installation, rated at 11.1 kW, generated 19.5MWh/year, contributing 92% of the total electricity production. In contrast, the DG generated 1,605 kWh/year (1.6MWh/year), accounting for 8% of the total output. The PV system has a capacity factor of 20% and a penetration rate of 32.2%, operating for 4,402 hours per year. The DG operated for 252 hours annually, with a capacity factor of 0.9%, consuming 368m^3 of fuel. It generated a maximum electricity output of 14 kW with a mean electrical efficiency of 44.3% and a specific fuel consumption rate of 0.23m^3 per kWh. The operational life of the DG is estimated at 119 years, indicating it can supply power for more than three times the lifespan of this system. The Figure 25 below shows the monthly electricity generation profile of the two power sources in the system.

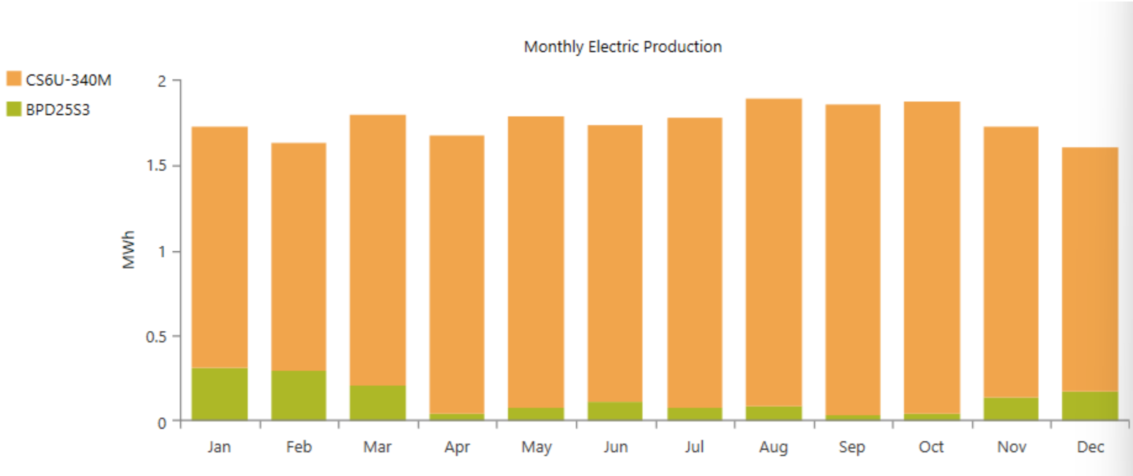

Figure 25: Monthly Electricity Production

From the **Figure** 25 above showing the monthly electricity production from PV and DG, it is evident that DG generation was higher between December and April, likely due to cloudy skies during the rainy season in the region, which limited the PV systems' ability to charge the batteries enough to meet the load demand in times of insufficient generation.

Power Output and Electrical Demand Balance

The **Figure** 26 below illustrates how the system balances load during October, the month with the highest PV generation, and how the dispatchable source, DG, responds to changes in demand. The generator operated for fewer hours in October compared to February as shown in **Figure** 27, as October experiences higher solar radiation, resulting in greater PV output. Conversely, in February, lower solar radiation necessitates more frequent use of the generator. The system meets demand using BESS and DG during periods of low PV generation, particularly at night when PV output is zero, demonstrating the system's reliability and adaptability to changing conditions.

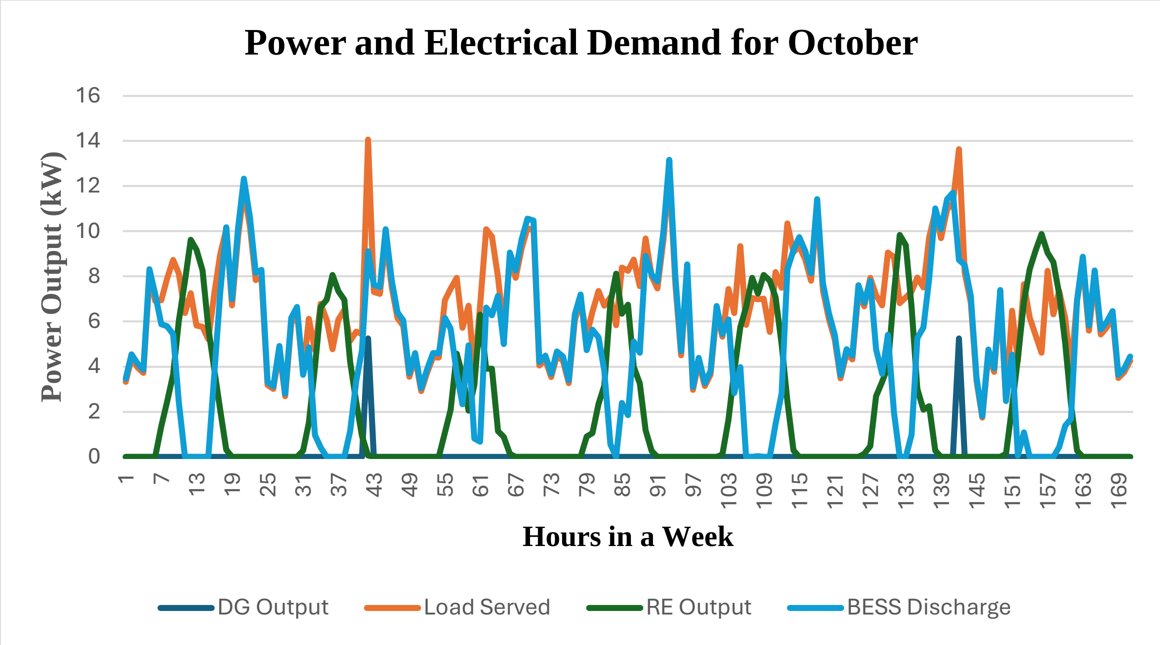

Figure 26: Power and Electrical Demand for October

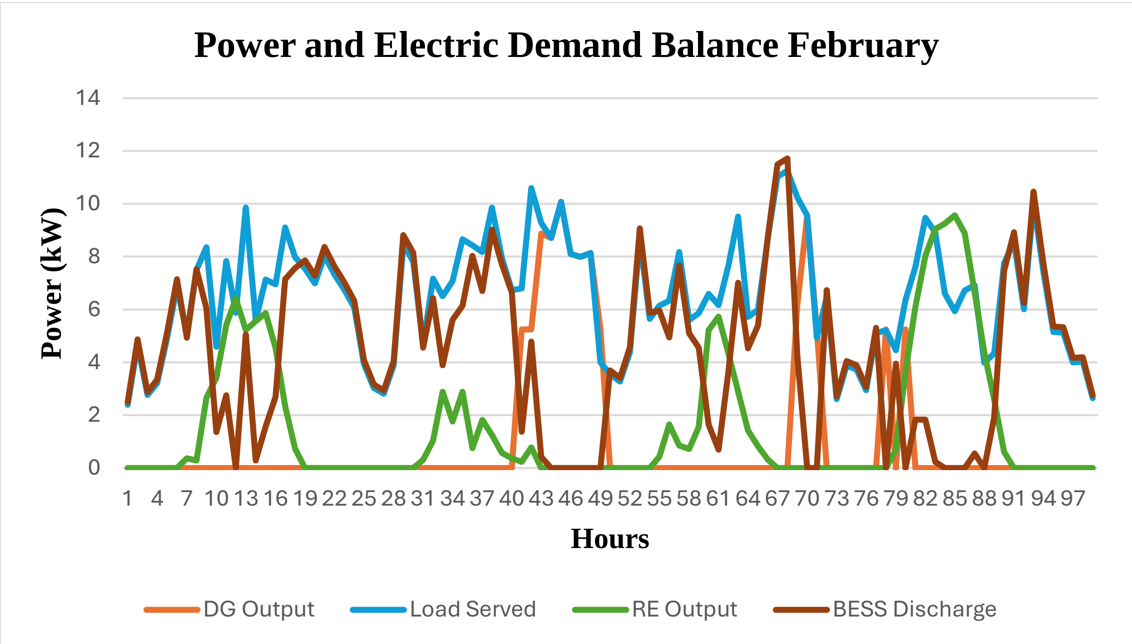

Figure 27: Power and Electric Demand in February

Power generation and Battery State of Charge

Like all scenarios in this study, for this hybrid scenario 2 simulation load following dispatch strategy was applied which means the generator operation was only used to supply power to load not charging batteries to reduce runtime and fuel consumption. For this reason, on presenting battery state of charge and power output results, DG generation is not included only RE output are included.

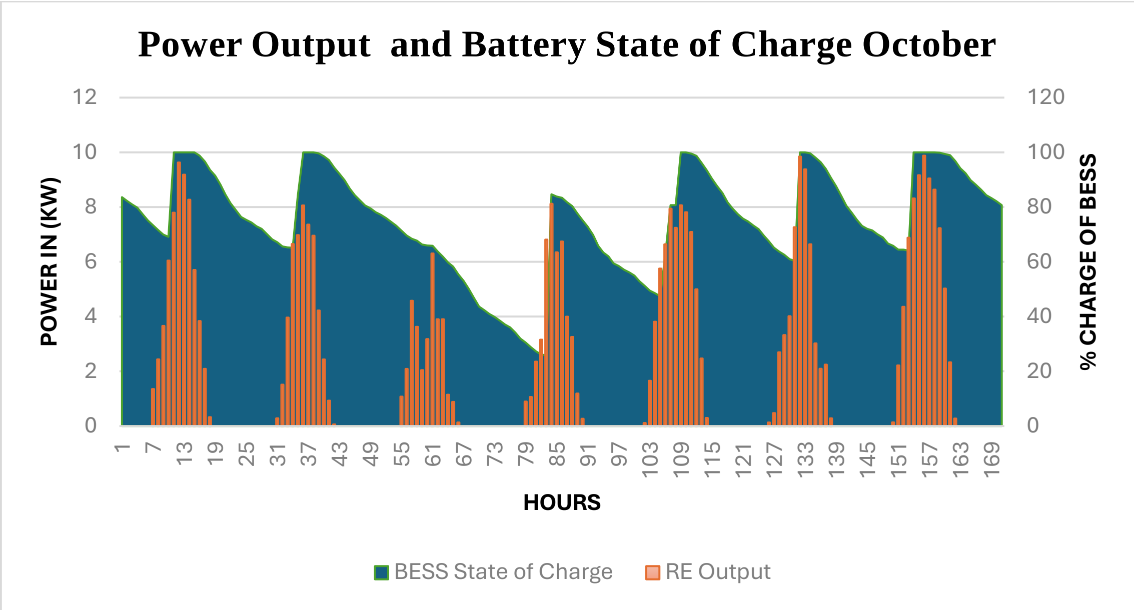

Figure 28: Power Output and Battery State of Charge October

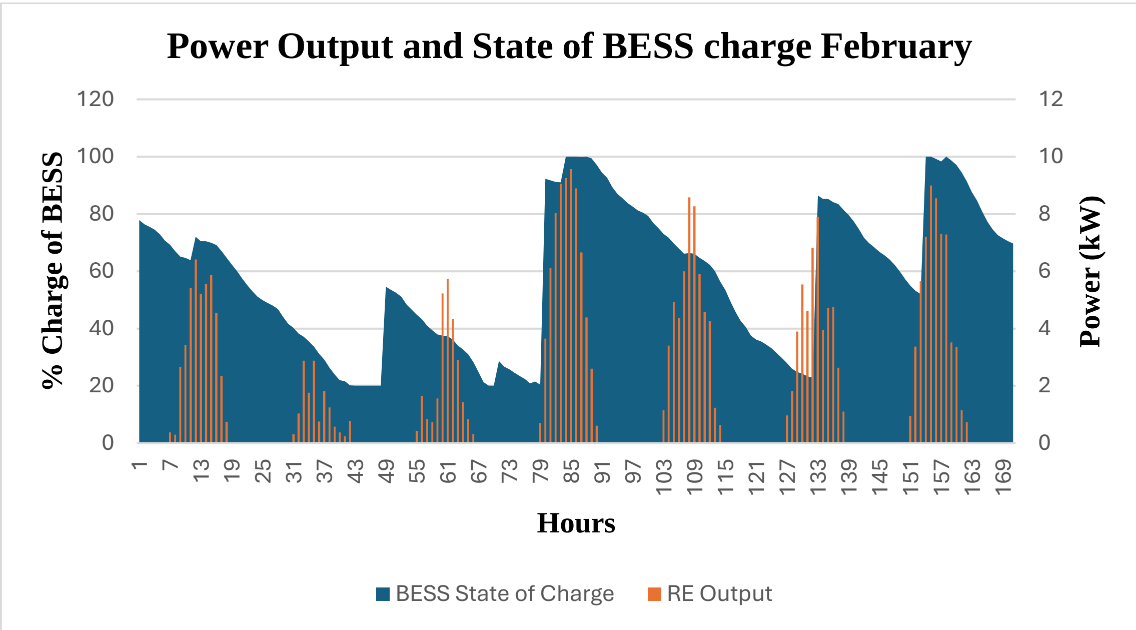

Figure 29: Power Output and Battery State of Charge February

From the Figure 28 and Figure 29, there is notable difference in the Battery Energy Storage System (BESS) state of charge can be observed between October and February. In October, the battery frequently reached 100% charge on most days, whereas in February, the BESS rarely achieved full capacity.

This pattern suggests that excess energy was likely generated between August and November, primarily due to high photovoltaic (PV) generation during these months. The abundant solar energy during this period provides a high quality of charge for the BESS.

Furthermore, this observation helps explain the increased Diesel Generator (DG) usage in February. With less solar energy available and lower BESS charge levels, the system relies more heavily on the DG to meet energy demands during this month.

Again, it can be observed that batteries in October were not fully utilised unlike in February which shows the DoD reached 20% for some days but this would be due to poor charge that the BES received because of low solar radiation.

Scenario 2 Costs Results

The initial capital investment for this system is $48,000.00 with a Net Present Cost (NPC) of $110,000.00 Over the project's 25-year lifespan, it achieves a Levelized Cost of Energy (LCOE) of $0.103/kWh, which is considered affordable compared to existing systems in the region. Analysis of the system costs reveals that PV panels and Li-ion battery contribute significantly to initial capital investment and replacement costs, while the Diesel Generator incurs higher operational costs due to fuel consumption. The BESS has high salvage value as they must be replaced midway of the project life span. The

Table 14 and Figure 30 below has systems costs details of scenario 2.

Component	Capital ($)	Replacement($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$8,400.00	$0.00	$88.34	$10,325.75	-$3,214.98	$15,599.11
CS6U-340M PVs	$17,944.11	$0.00	$31,111.90	$0.00	$0.00	$49,056.01
System Converter	$7,000.00	$3,920.27	$2,103.34	$0.00	-$2,543.50	$10,480.11
Li-ion Battery	$13,500.00	$7,560.51	$3,155.01	$0.00	-$4,905.31	$19,310.21
Other	$800.00	$0.00	$14,022.27	$0.00	$0.00	$14,822.27
System	$47,644.11	$11,480.78	$50,480.86	$10,325.75	-$10,663.79	$109,267.71

Table 14: Scenario 2 System Components Costs

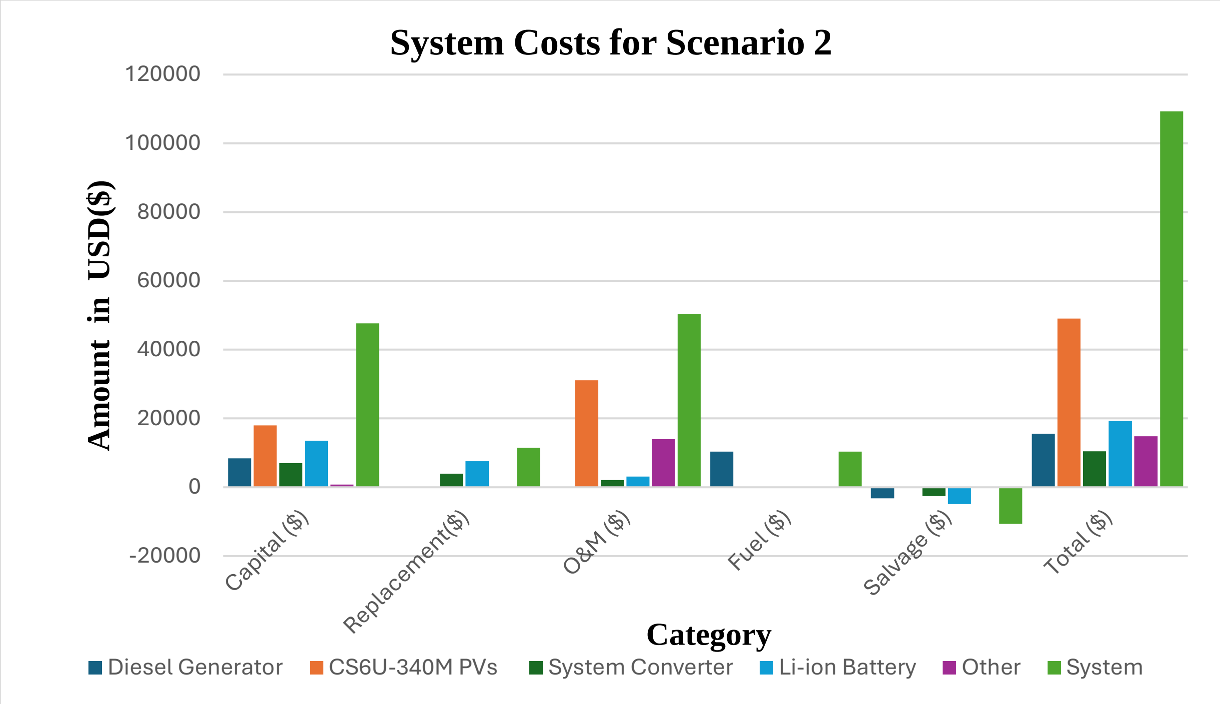

Figure 30: System Costs for Scenario 2

Energy Security

This scenario includes more than two generation sources, with one being dispatchable, enhancing energy security compared to Scenario 1. In the event of a failure in one generation source or prolonged severe climate conditions affecting solar PV output and battery charge, the presence of multiple sources ensures that another generation source can compensate when storage is depleted, thereby reliably meeting load demand.

Emissions

The system generating over 90% of its power from renewables. However, the inclusion of a Diesel Generator (DG) increased CO_2 emissions from 0 kg/year in a fully renewable system to 973 kg/year. While these emissions are higher than in purely renewable systems, they are lower than those from systems relying solely on diesel generators. The Table 15 has detailed information of all emissions produced by the system in a year.

Component	Value
Carbon Dioxide	973kg/yr
Carbon Monoxide	0.239kg/yr
Unburnt hydrocarbons	0.151kg/yr

Particulate Matter	0.0773kg/yr
Sulphur Dioxide	2.41kg/yr
Nitrogen Oxides	7.14kg/yr

Table 15: Emissions from the System

4.2.3 Scenario 3: Solar PV – Wind Turbine – Battery Storage

The Figure 31 shows the schematic of scenario 3 which depicts a hybrid energy system configuration. In this setup, the load demand is connected to the AC side, along with a wind turbine. A bidirectional converter linking between the AC and DC components, facilitating the necessary current type conversions. On the DC side, a bus connects the photovoltaic (PV) panels and the Battery Energy Storage System (BESS).

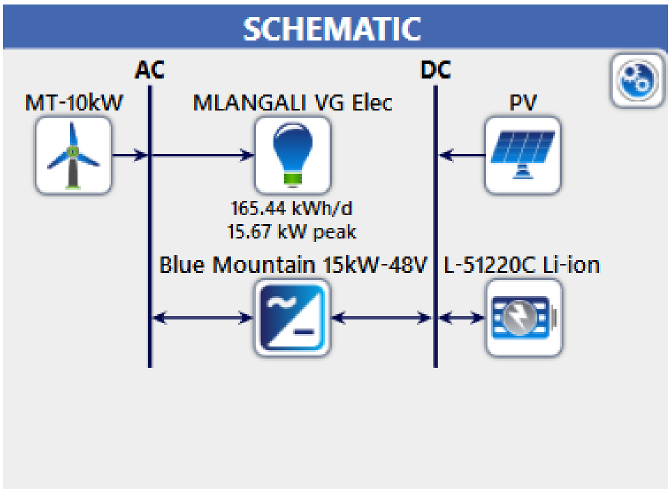

Figure 31: The Schematic of Scenario 3

Scenario 3 System Performance Results

Power Generated for the System

The results of Scenario 3 indicate that the total power generated per year by Solar PVs and a wind turbine is 38.8MWh, with Solar PVs contributing 18.9MWh, equivalent to 49%, and the wind turbine contributing 19.9MWh, equivalent to 51%. The system produced 22.8% excess energy, translating to 8.9 MWh/year, with an unmet load of 0.03%. The system achieved a 100% renewable energy fraction. The Solar PVs were rated at 10.8 kW, operating for 4402 hours per year, while the wind turbine was rated at 10 kW, operating for 7719 hours per year. The **Table** 16 below has main results of the scenario system simulation.

Characteristic	Value
Renewable Fraction (%)	100
LCOE ($/kWh)	0.16
CO_2 Emissions (kg/year)	0
Net Present Cost ($)	167,000.00
Initial Capital Cost ($)	93,000.00
Unmet Electric load (%/year)	0.003
Excess Electricity (%/Year)	22.8
Total power generated (MWh/year)	38.8

Table 16: Scenario 3 Main Results

The system initially suggested one 16.1 kW converter. Choice was made to use two 15 kW converters instead. This gives extra safety and room for system expansion if need arises. It also protects against power surges and overloading. For this scenario simulation all components of the system except the converters were optimised by HOMER. The Table 17 below shows a summary of all system parts, their individual sizes, and the total system size.

Component	Quantity	Rating(kW)	Power Generated
CS6U-340M PVs(0.340kW)	32	10.8	18.9MWh/yr
Wind Turbine (MT-10kW)	1	10kW	19.9MWh/yr
Converters (15kW)	2	15	_
Li-ion Batteries(11.26kWh)	6	68	_

Table 17: Scenario 3 Components Quantities

From the Figure 32 below, it can be observed that more power was generated between July and November, with October being the peak month, reaching 5 MWh. The results suggest that a substantial amount of excess energy was generated during these months. This could be attributed to the load demand and storage capacity being insufficient to consume the generated power, leading to excess energy.

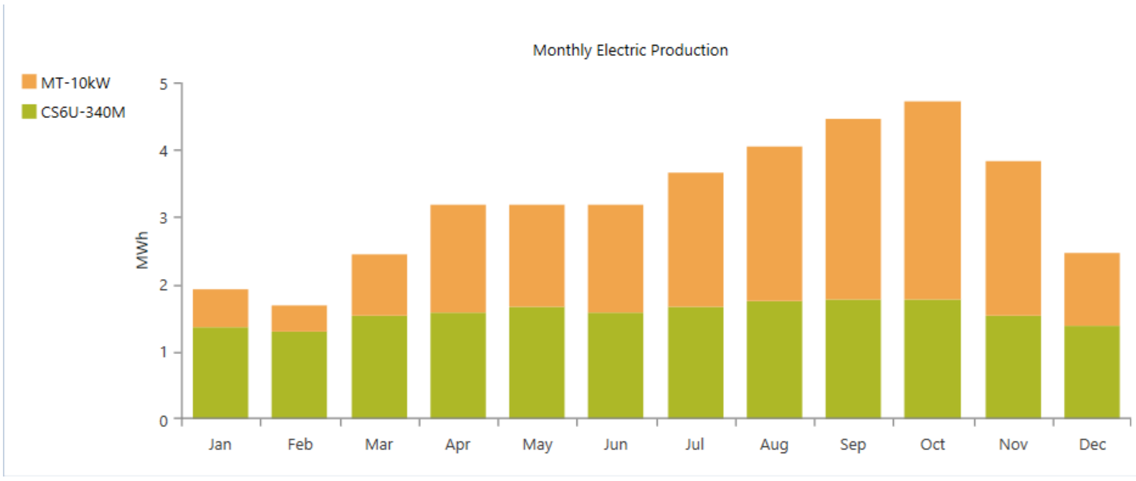

Figure 32: Monthly Electricity Production

Power Output and Load demand Balance

The results from the first week of October, as depicted in Figure 33 demonstrate the system's ability to provide uninterrupted energy supply using the backup Battery Energy Storage System (BESS). When power output from generation sources experiences sudden drops, the BESS discharges power to compensate for the deficit, effectively functioning as a buffer during periods of insufficient generation to meet demand. This behaviour illustrates the system's reliability and resilience, showcasing its capacity to maintain continuous power supply even in the face of fluctuations in primary generation sources. The BESS's role in smoothing out these variations enhances the overall stability and dependability of the power system, ensuring consistent energy delivery to meet demand

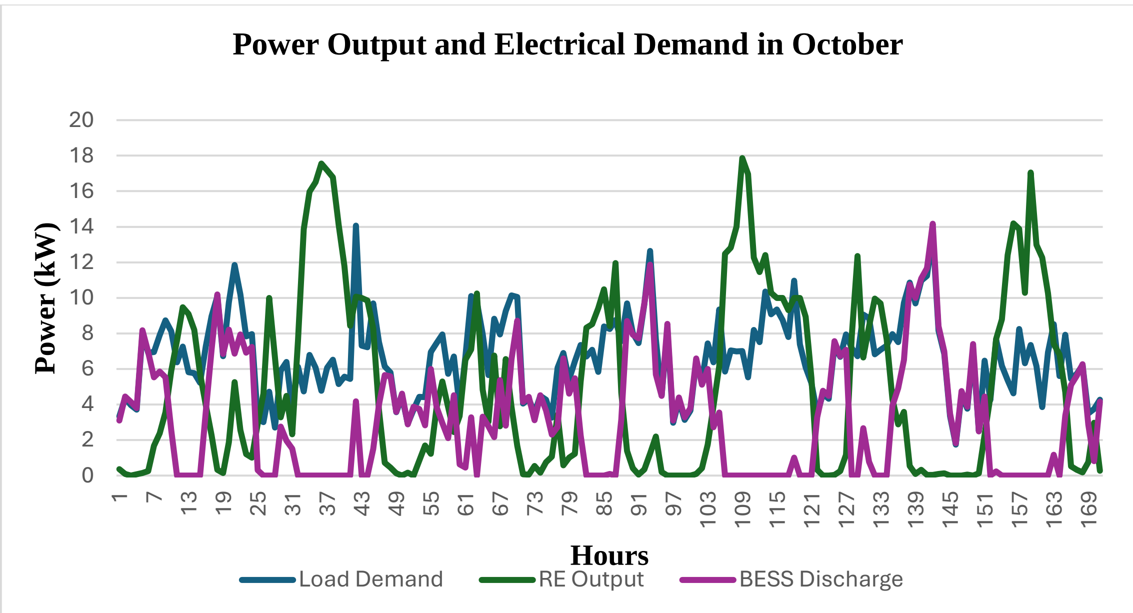

Figure 33: Power and Demand Balance October

The results from first week of February shown in Figure 34 demonstrate the system's consistent behaviour during the month of lowest power generation due to low radiation and low wind speed. Despite these challenging conditions, the system maintained its reliability, showcasing its ability to provide a stable energy supply to the community.

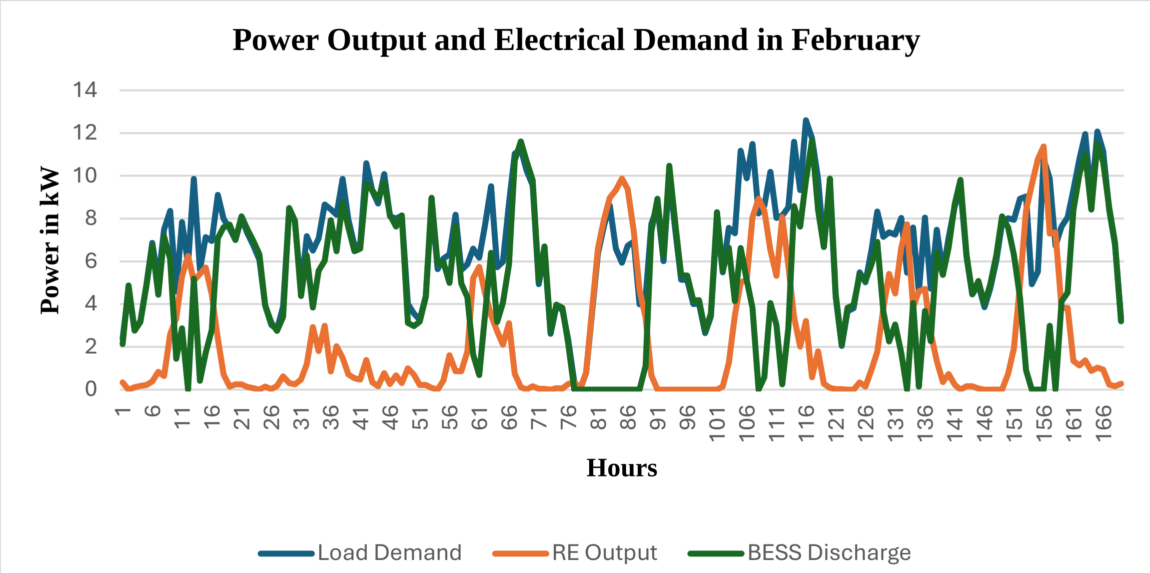

Figure 34: Power and Load Demand Balance February

Power Generated and BESS state of Charge

In October, strong winds and plenty of solar radiation helped the renewable systems generate a lot of power, making the battery reach 100% charge most of the time. In February, both wind and solar power were lower, so the battery often did not reach full charge. However, even in February, the battery got enough energy to keep the system powered during insufficient generation of power. The Figure 35 and Figure 36 shows the

BESS state of charge in month of low generation February and month of high generation in October.

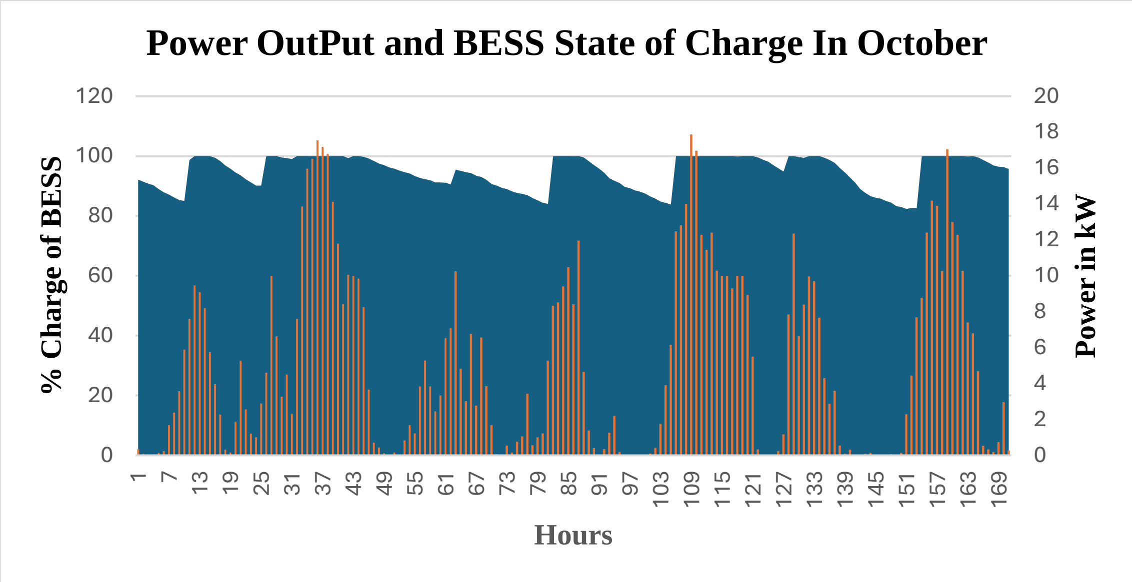

Figure 35: Power Output and BESS State of Charge in October

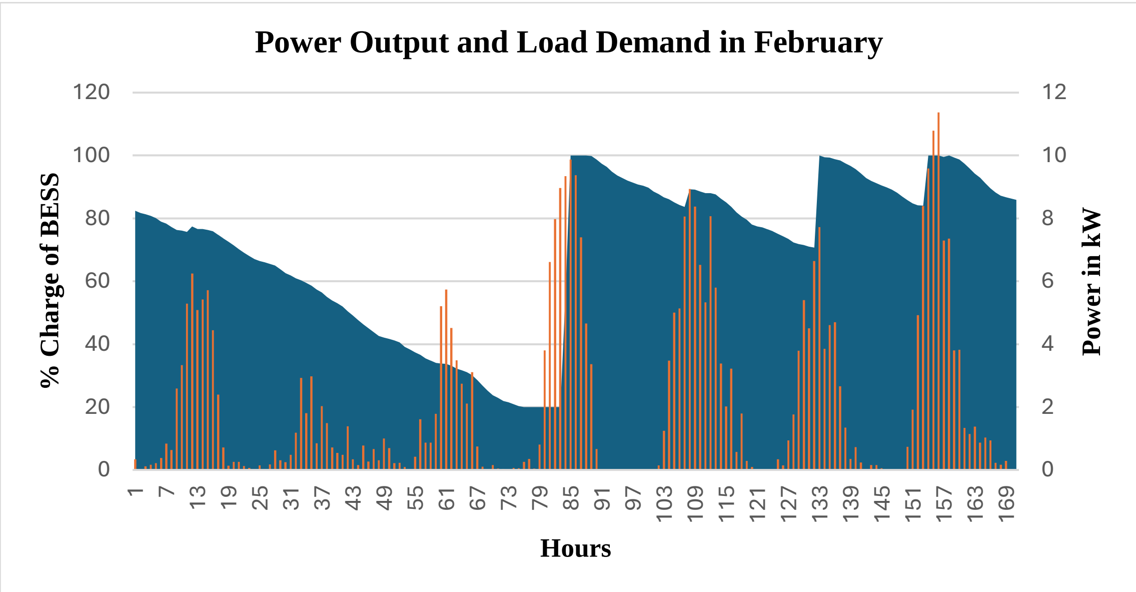

Figure 36: Power Output and BESS State of Charge in October

In this scenario, battery usage is very poor, particularly in October, when discharge levels rarely exceed 80%. Similarly, in February, discharge levels barely reach 70% on most days. This may be attributed to the wind turbine generating power at night, reducing the need for battery discharge, and indicating that the battery bank may be oversized for the system, despite being recommended by HOMER optimisation.

Scenario 3 System Costs Results

The system's initial capital expenditure is estimated to be $93,000.00, with a net present value of $167,000.00, producing a levelized cost of energy (LCOE) of $0.16/kWh, which is lower compared to the existing price of electricity in isolated minigrids. The Table 16 and

Table 18 has details of key results of system components costs.

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
CS6U-340M	$17,495.57	$0.00	$30,334.19	$0.00	$47,829.76
System Converter	$7,000.00	$3,920.27	$2,103.34	-$2,543.50	$10,480.11
Li-ion Battery	$27,000.00	$15,121.02	$6,310.02	-$9,810.63	$38,620.42
Wind Turbine	$40,000.00	$17,921.21	$8,763.92	-$11,627.41	$55,057.72
Other	$800.00	$0.00	$14,022.27	$0.00	$14,822.27
System	$92,295.57	$36,962.50	$61,533.74	-$23,981.54	$166,810.27

Table 18: Scenario 3 System Components Costs

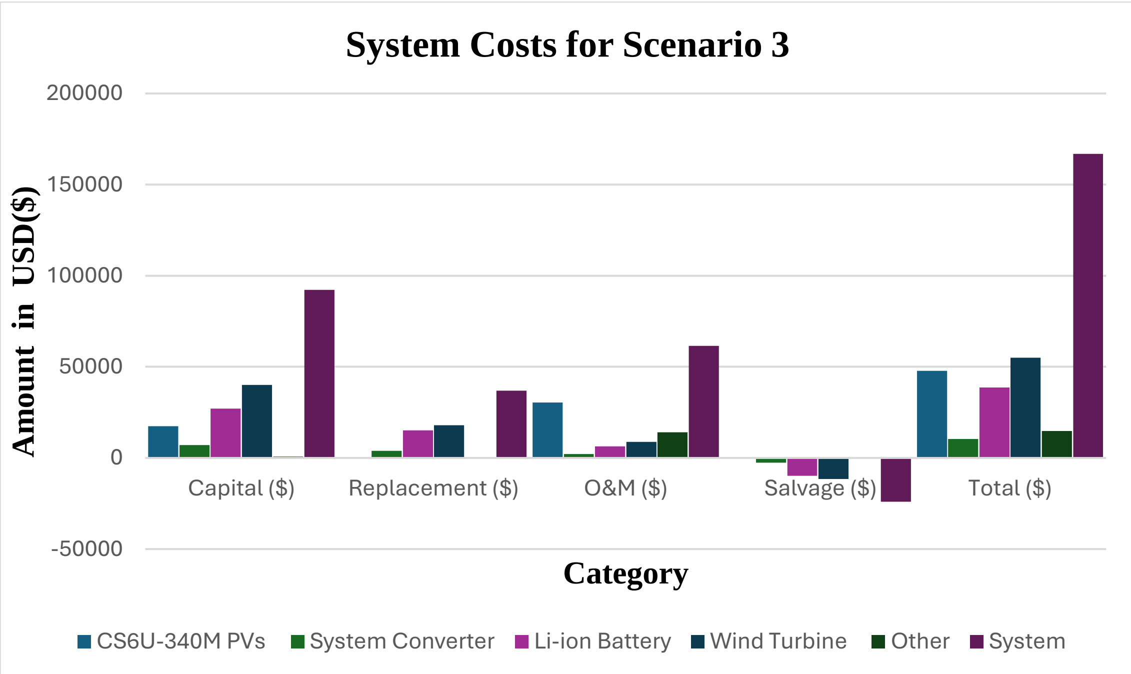

Figure 37: System Costs for Scenario 3

Table 18 and Figure 37 show the system's cost breakdown. Wind turbines cost the most to buy initially, followed by batteries and solar panels. Batteries and wind turbines are also expensive to replace. Solar panels have the highest ongoing maintenance costs. These different costs affect the overall value of the system (Net Present Value) and the price of the electricity it produces (Levelized Cost of Energy).

Energy Security

The scenario has 2 generation sources solar and wind plus the BESS making it secure. The only challenge that may exist when the weather is challenging affecting both wind and solar which may happen but in rare cases.

Emissions

This scenario has 100% percent renewable Fraction Therefore no greenhouse gas emissions were recorded for this scenario simulations.

4.2.4 Scenario 4: Solar PV- Wind turbines- Diesel Generator -Battery Storage

The **Figure** 38 is the schematic of scenario 4 which features a system that includes a diesel generator (DG), a wind turbine, PV panels, and a Battery Energy Storage System (BESS). The DG and wind turbine are connected to an AC bus, while the PV panels and BESS are linked to a DC bus, which is connected to the AC bus via a converter. This converter changes the DC current from the PV panels and BESS into AC current to meet the load demand, which requires AC type current.

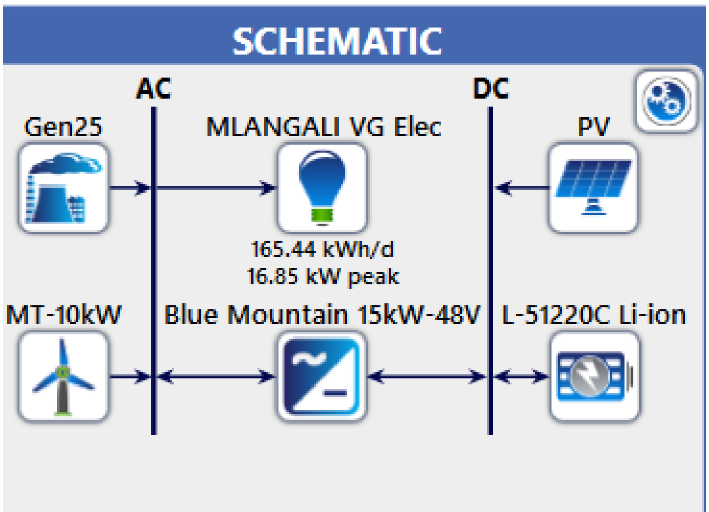

Figure 38: The Schematic of Scenario 4

Scenario 4 System Performance Results

Total Power Generated

The results indicate that the system generated a total of 27.7MWh/year, with 12.2%/year excess electricity and 0%/year unmet load demand. The diesel generator contributed 2.2MWh per year equivalent to 8% of the generated electricity, solar PV contributed 5.7MWh per year translating to 20% while the wind turbine generated 72% which is 19.9MW. Despite using the diesel generator as a dispatchable source, the system achieved a 96% renewable power fraction, allowing the generator to run for only 348 hours in a year consuming 502 litters of fuel with 44% electrical efficiency.

Key results from the scenario simulation are presented in the **Table** 19 and Table 20 below.

Characteristic	Value
Renewable Fraction (%)	96.3
LCOE ($/kWh)	0.13
CO_2 Emissions (kg/year)	1,358
Net Present Cost ($)	134,000.00
Initial Capital Cost ($)	75,000.00
Unmet Electric load (%/year)	0
Excess Electricity (%/Year)	12.5
Total power generated (MWh/year)	27.7

Table 19: Scenario 4 Main results

The Table 20 has results for the number of components used in the system for the entire lifespan of the project. It has been observed that HOMER optimizer goes for system operation that will produce lowest Net Present Value in this case the wind has been fully utilised compared to the PV which generated only 20% of electricity the whole year which shows that within this scenario generating more electricity from wind and Diesel Generator as dispatchable source supplemented by BESS is cheap option. Again, initial optimisation recommended 17.1kW converter but choice was made for two 15kW converters for safety purposes using search space function while optimising all other components.

Component	Quantity	Rating(kW)	Power Generated
CS6U-340M PV(0.34kW)	10	3,22	5.7MWh/yr

Wind Turbine (MT-10kW)	1	10	19.9MWh/yr
Converters (15kW)	2	30	_
Diesel Generator(21kW)	1	21	2.2MWh/yr
Li-ion Batteries(11.6kWh)	3	34	_

Table 20: Scenario 4 Components Quantities

From Figure 39 below, it can be observed that wind power generation peaked from July to November, coinciding with the period of highest wind speeds and solar radiation in the region. October saw the maximum output, reaching over 3.5MWh of power generated.

This seasonal pattern significantly impacted the overall energy balance of the system. The result suggests that a substantial portion of the 12.5% excess energy was likely produced during this high solar-wind period. During these months, several factors contributed to the energy surplus: elevated PV and wind turbine output due to favourable solar and wind conditions, batteries reaching full charge capacity and load demand being fully met. below to.

As a result, the system generated more power than could be immediately consumed or stored, leading to excess energy production. During the months outside of December to March, wind speeds were lower than usual. This reduction in wind speed resulted in decreased power generation from wind turbines. As a result, diesel generators (DG) had to operate for longer hours to compensate for the inadequate power produced by wind sources, ensuring sufficient electricity supply to meet demand.

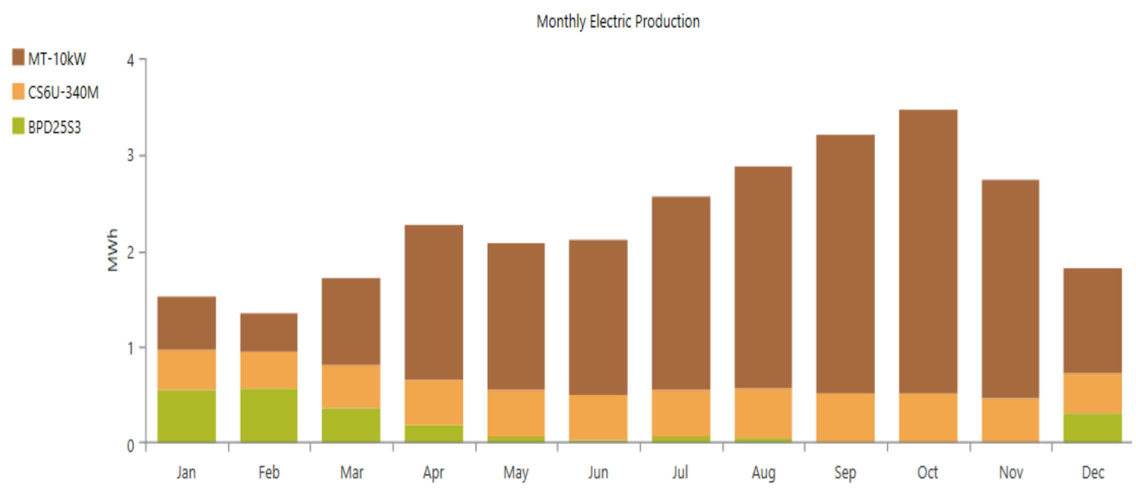

Figure 39: : Monthly Total Power Generated

The Figure 40 shows how wind speed affects the system's performance. The data take from first week of October, when wind speeds are highest, leading to the best wind turbine output. During this time, the generator ran for fewer hours compared to winter months (December to March). The graph reveals that when wind speeds are very high, the power output stays the constant and drops when wind speed is above certain threshold. This is because wind turbines have specific speed ranges where they work best. If the wind is too slow or too fast, it affects how much power the turbine can produce.

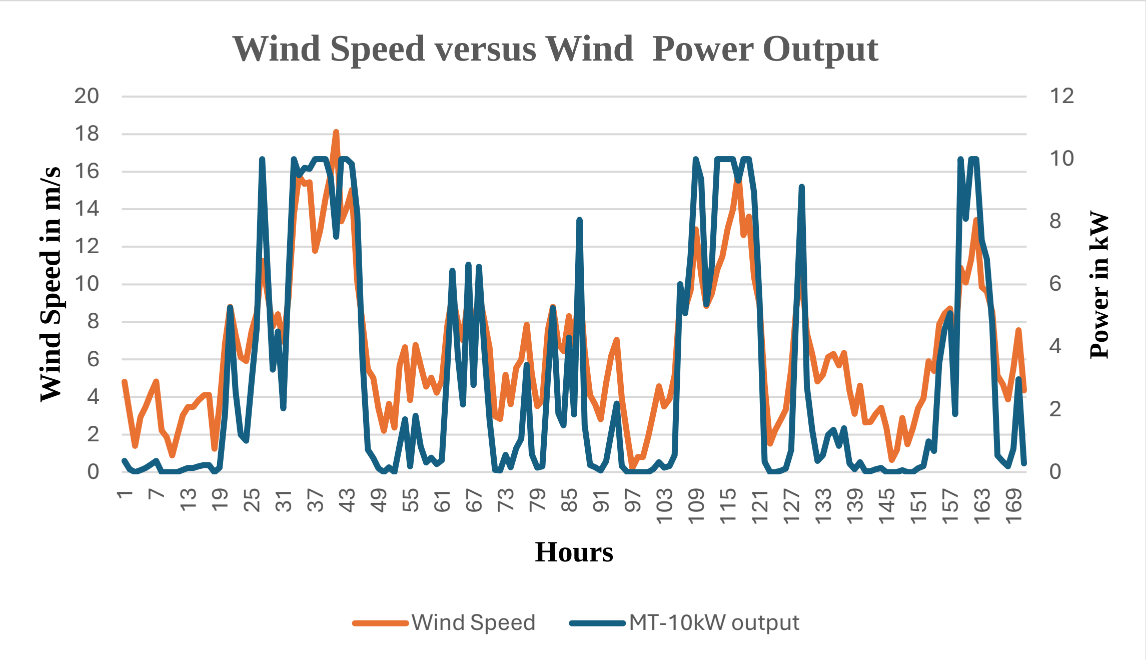

Figure 40: Wind Speed vs Power Output

Power Output and Load Demand Balance

The plot in Figure 41 illustrates the system's performance in meeting the community's energy demand. During periods of low PV or wind turbine output, the Battery Energy Storage System (BESS) discharges stored power to supplement the generation sources, thereby ensuring that the load demand is consistently met. DG only comes in when both generation and BESS fail to meet demand though for this plot DG was zero throughout. This coordination between the wind turbine and BESS highlights the system's capability to maintain a reliable power supply.

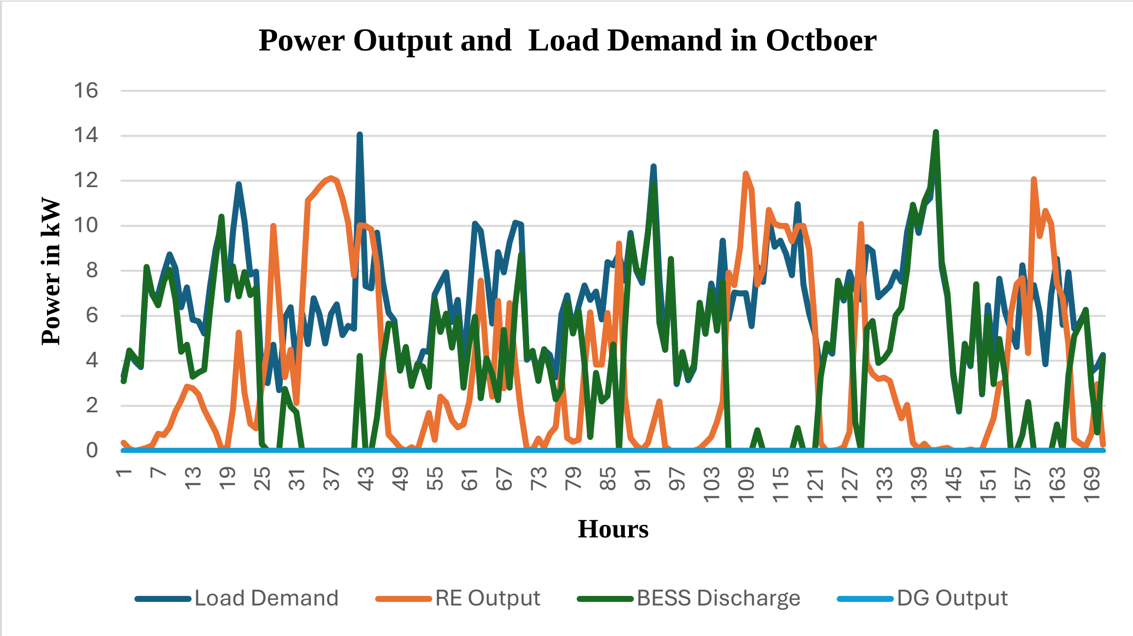

Figure 41: Scenario 4 Power Output & Load Demand in October

The Figure 42 illustrate the behaviour of the system during 48hrs in the month of February when solar radiation and wind speed is very low. When solar PV and wind turbine output is insufficient BESS and DG function as backup systems supplying power to meet the load demand of the community. This demonstrates the resilience and reliability of the system.

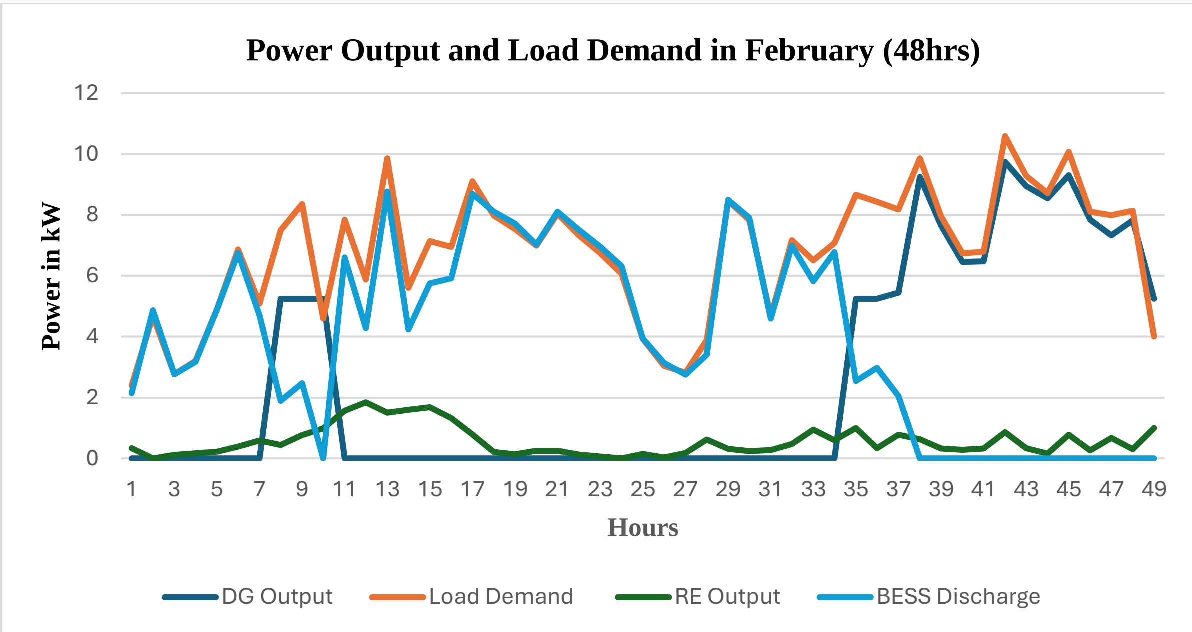

Figure 42: Scenario 4 Power Output & Load Demand

Power Generation and BESS State of charge.

The Figure 43 and Figure 44 showing how power generation affect quality of BESS charge during October the batteries receive ahigh quality charge reaching full capacity unlike in February when BESS charge does not reach full capacity on most occasions.

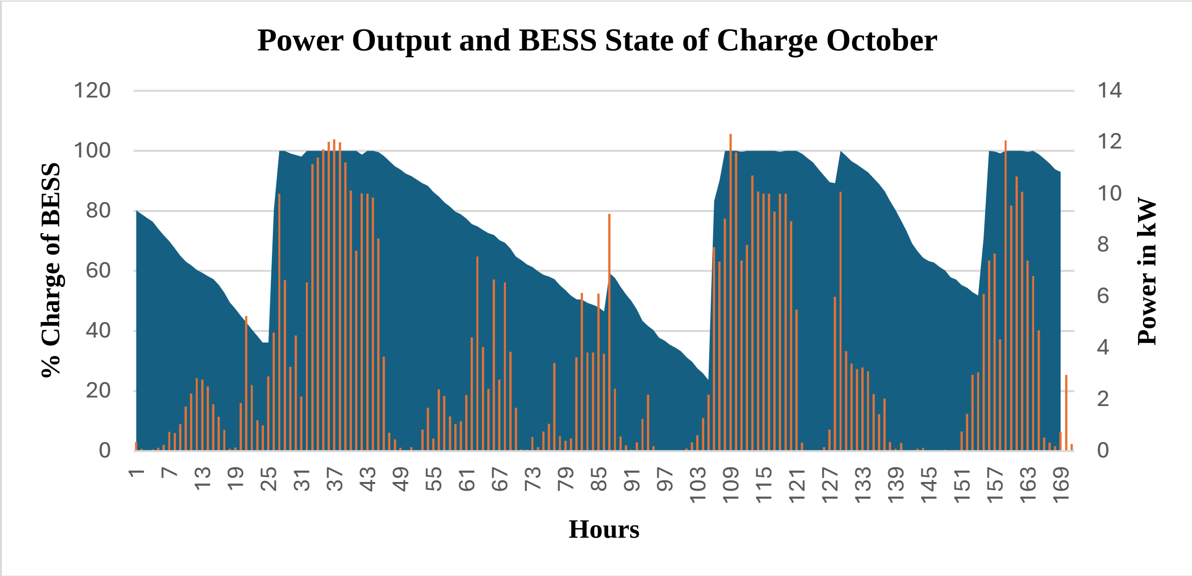

Figure 43: Power Output and BESS State of Charge October

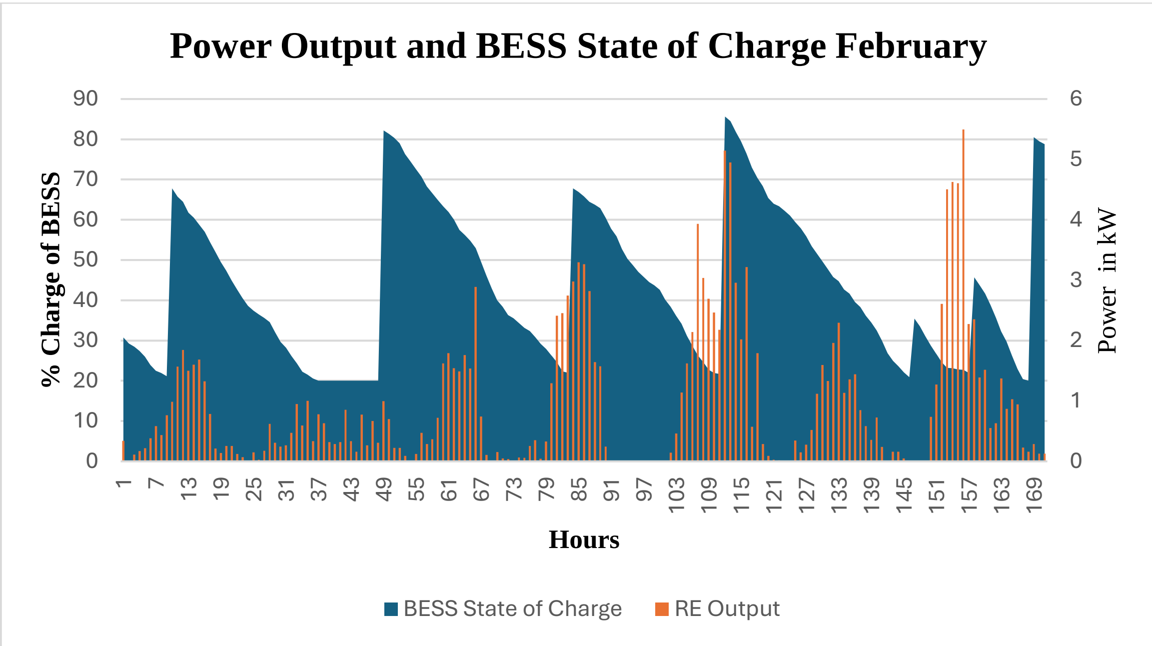

Figure 44: Power Output and BESS State of Charge February

This scenario BESS is well performing system when compared to other scenarios especially in February when the battery bank reaches the DoD limit of 20% on most days which explains makes it a well optimised system.

Scenario 4 System Costs Results

The system's initial capital expenditure is estimated at $94,000.00, with a net present value of $134,000.00 and levelised cost of $0.13/kWh which is lower when compared to existing prices of electricity generated by solar and other independent power producers.

In an ideal scenario, it might be expected that a system combining all three generation sources (solar, wind, and diesel) to have the highest capital investment and Net Present Value (NPV), consequently leading to a high Levelized Cost of Energy (LCOE). However, contrary to this expectation, the observed system components cost, capital cost, NPV and LCOE are significantly lower than those of the scenarios utilising only wind and solar with battery energy storage (BESS).

This result can be attributed to the increased storage requirements in systems relying solely on intermittent renewable sources. A system with only photovoltaics (PVs) and wind requires more storage batteries to ensure consistent power supply during periods of low generation. In contrast, a system incorporating a dispatchable source (such as a diesel generator) can operate with fewer batteries, as the generator can provide power on demand.

The Table 21 and Figure 45 provide detailed information on all system components and the costs incurred over the project's lifetime.

Component	Capital($)	Replacement($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Diesel Generator	$8,400.00	$0.00	$124.45	$14,411.75	-$2,865.67	$20,070.53
CS6U-340M PVs	$5,160.58	$0.00	$8,947.43	$0.00	$0.00	$14,108.01
System converter	$7,000.00	$3,920.27	$2,103.34	$0.00	-$2,543.50	$10,480.11
Li-ion Battery	$13,500.00	$7,560.51	$3,155.01	$0.00	-$4,905.31	$19,310.21
Wind Turbine	$40,000.00	$17,921.21	$8,763.92	$0.00	-$11,627.41	$55,057.72
Other	$800.00	$0.00	$14,022.27	$0.00	$0.00	$14,822.27
System	$74,860.58	$29,401.99	$37,116.41	$14,411.75	-$21,941.90	$133,848.84

Table 21: Scenario 4 System Components Costs

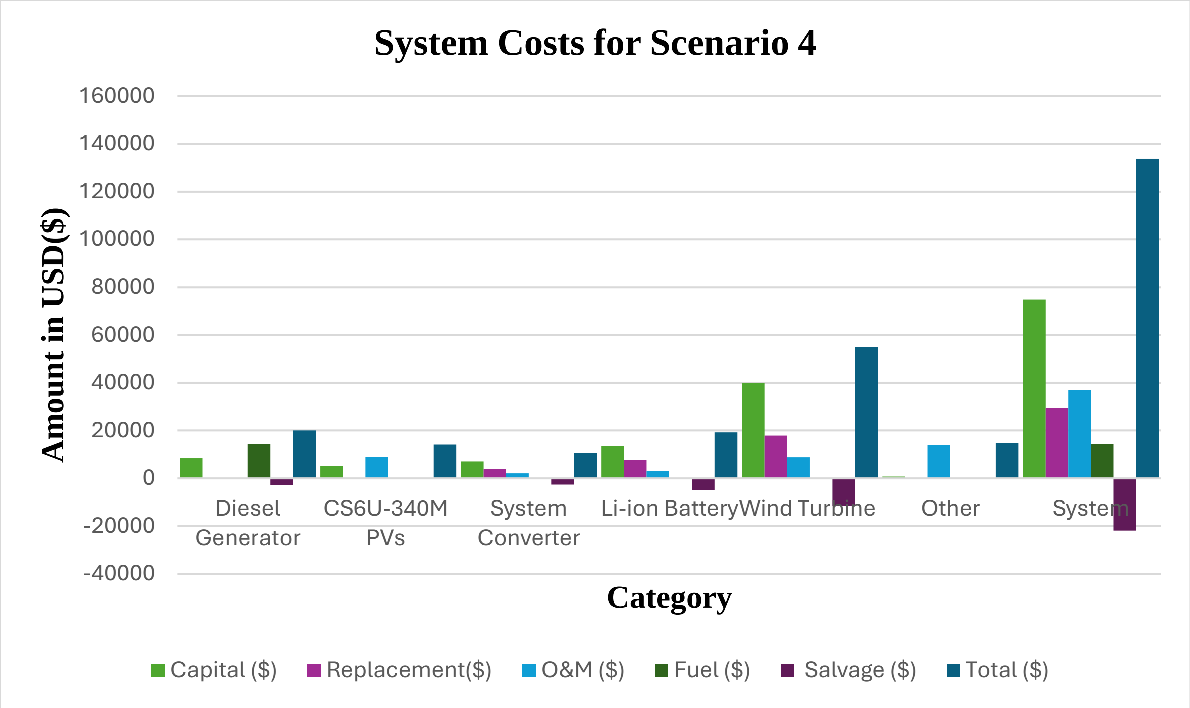

Figure 45: System Components Costs

Energy Security

This scenario is the most secure system with 3 generation sources and BESS making it stable and reliable. the challenge is that its complex making it hard to maintain.

Emissions

The inclusive of DG in scenario resulted in CO_2 emissions of 1327kgs/year. The Table 22 below has details of all emissions released by the DG throughout 1 year operation.

Component	Value
Carbon Dioxide	1327kg/yr
Carbon Monoxide	0.326kg/yr
Unburnt hydrocarbons	0.206kg/yr
Particulate Matter	0.105kg/yr
Sulphur Dioxide	3.29kg/yr
Nitrogen Oxides	9.74kg/yr

Table 22: Scenario 4 Emissions

3.3 Scenarios Evaluation

In this section all scenarios will be evaluated based economic analysis, performance in terms of access and energy security, resilience and adaptability of the system.

1. **Economic Analysis**

The systems simulated in this study are designed for implementation in rural, isolated settings where communities struggle to meet necessities. Supplying electricity to these areas could significantly enhance their means of survival. For these communities, it is important to consider the economic aspects of such projects. The Figure 46 and Figure 47 below illustrates the economic comparisons for all scenarios using capital cost (CAPEX), net present cost (NPC), and levelized cost of energy (LCOE).

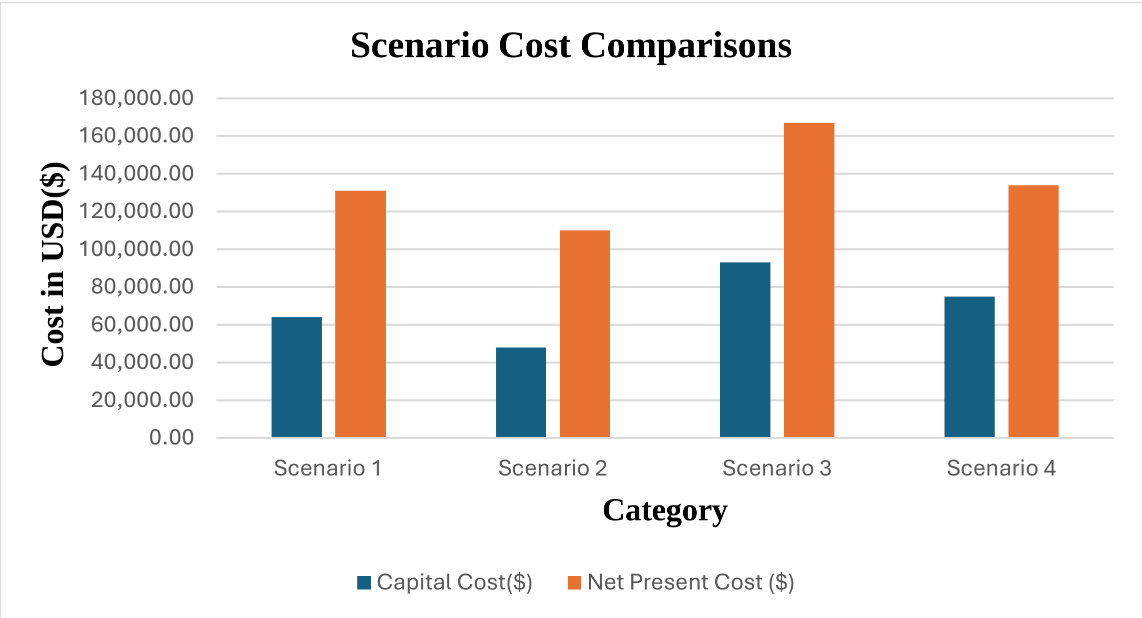

Figure 46: Scenario Cost Comparisons

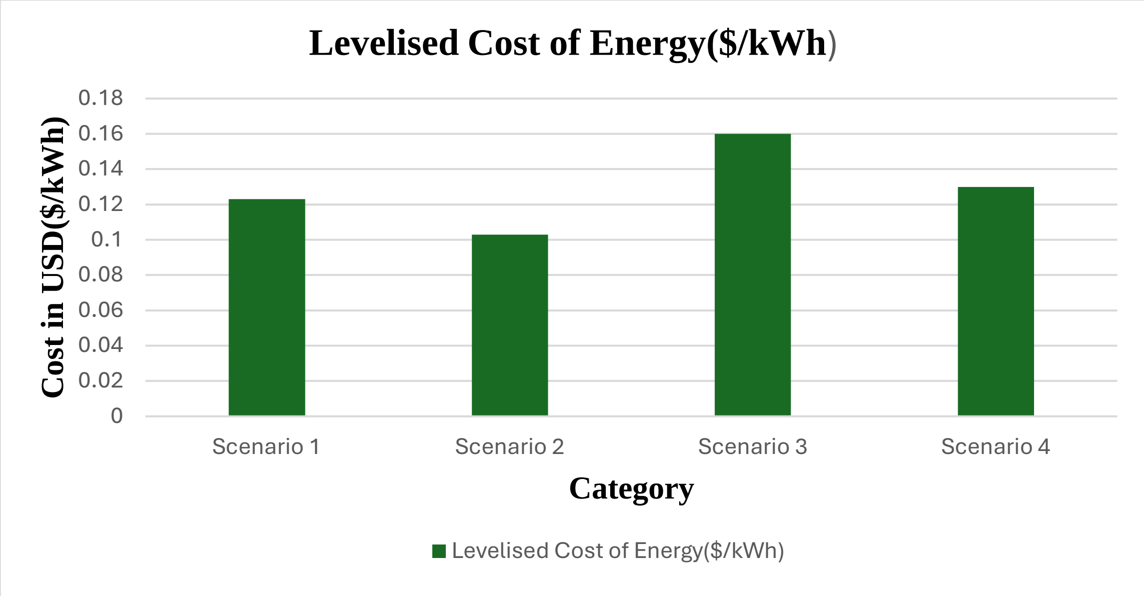

Figure 47: Levelised Cost of Energy($/kWh)

Overall, scenarios that included a Diesel Generator (DG) demonstrated lower capital costs net present costs, and levelized costs of energy in relation to the number of components in the system. For example, the inclusion of a DG in scenario 1 to create scenario 2 was expected to increase CAPEX, NPC, and LCOE. However, contrary to expectations, there was a significant reduction in costs, making scenario 2 more affordable than scenario 1, despite having more power generation sources. A similar situation was observed between scenario 3 and scenario 4 when DG was included in scenario 3 to create scenario 4. The Table 23 below show the costs of each scenario.

Component	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Capital Cost($)	64,000.00	48,000.00	93,000.00	75,000.00
Net Present Cost ($)	131,000.00	110,000.00	167,000.00	134,000.00
Levelised Cost of Energy($/kWh)	0.123	0.103	0.16	0.13

Table 23: Scenarios Economic Comparisons

This reduction in costs can be attributed to the inclusion of the DG, which reduced the need for more batteries and solar PVs. Batteries incur high replacement costs due to their short lifespan compared to the project duration, and solar PVs have high operations and maintenance (O&M) costs as they require regular checks for optimal efficiency. Another important observation is that although DGs have higher fuel costs, their integration with hybrid systems significantly reduces runtime, thereby lowering fuel expenditures. Based on the economic analysis, scenario 2 stands out as the most affordable option for the community.

2. **Energy Access**

The scenarios were designed to ensure 100% power access for the community. From the results previously discussed, it is evident that all scenarios successfully achieved full power access, with the 0.03% and 0.003% of unmet load in scenarios 1 and 3, respectively, being negligible. Scenario 3 generated more energy, producing 38.8 MWh/year, compared to Scenario 4's 27.7 MWh/year, Scenario 2's 21 MWh/year, and Scenario 1's 21.2 MWh/year.

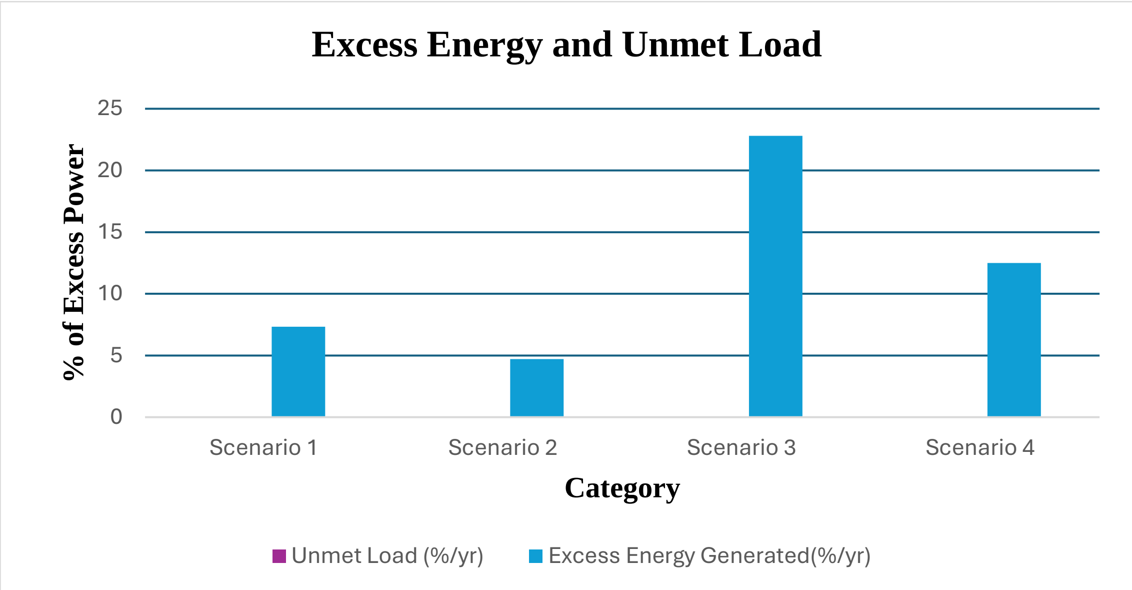

Figure 48: Excess Energy and Unmet Load

From the Figure 48 above Scenario 3 had a higher excess energy percentage of 22.8% and unmet load of 0.003% per year. While having excess energy in a system offers opportunities for load expansion, export and necessitates more storage space which may work better with grid connected micrograds, but for a system generating significant excess energy in isolated microgrid needs fine-tuning for optimal efficiency to minimize the surplus energy that goes to waste. Scenario 4 exhibited an excess energy of 12.5% with 0% unmet load per year, Scenario 2 had 4.7% excess energy with 0% unmet load per year, and Scenario 1 had 7.33% excess energy with 0.03% unmet load. The optimal system is one that meets 100% of load demand with minimal excess energy, making Scenario 2 the most efficient and effective among all the scenarios.

3. Energy Security

To ensure an uninterrupted supply of power to the community, it is essential to consider having backup systems that can function as a buffer during times of insufficient generation or system faults. All scenarios simulated in this study include at least one backup system to compensate for any shortfall in supply or system failures. Relying solely on a single generation source and storage as a backup may not guarantee a robust energy-secure system, as prolonged insufficient generation or system failures could deplete the storage, potentially causing the entire microgrid to go offline. The Table 24 below provides detailed information on all scenarios and their respective backup systems.

Component	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Solar PV	Yes	Yes	Yes	Yes
Wind Turbine	No	No	Yes	yes
Diesel Generator	No	Yes	No	Yes
Battery Energy Storage System	Yes	Yes	Yes	Yes
Total	2	3	3	4

Table 24: Scenarios and Backup Systems

From Figure 49 below, it is evident that scenario 4 system has robust energy secure configuration with 3 additional backup systems. Based on the number of backup systems scenario 4 surpasses scenario 1 with which as only single generation source and storage, scenario 2 and 3 with both having 2 generation sources and storage.

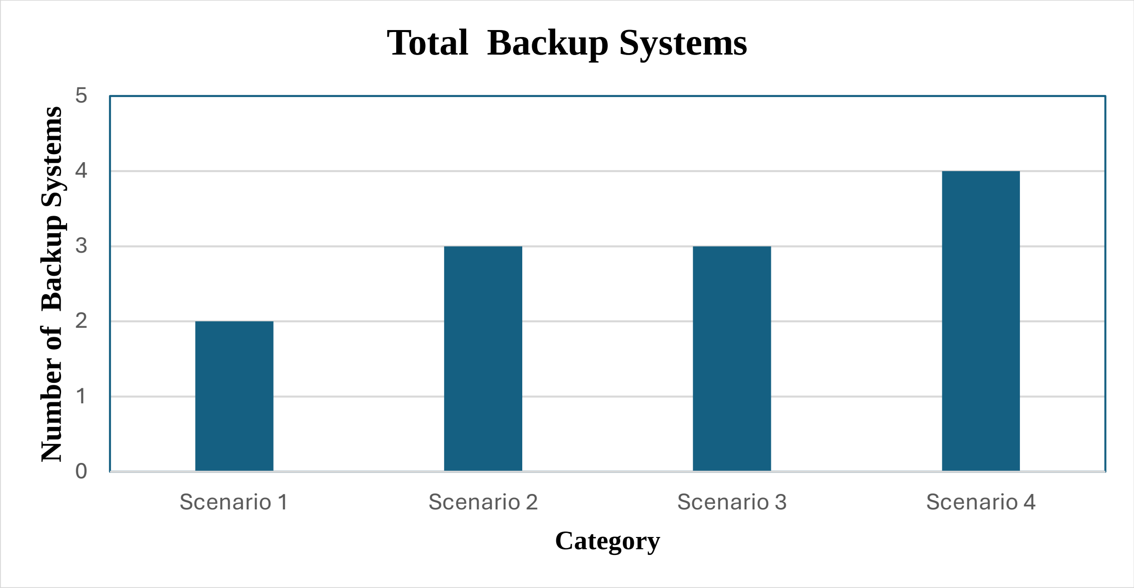

Figure 49: Total Backup Systems for each Scenario

4. **Environmental impact.**

Comparison has been made to the base case scenario where a standalone diesel generator was simulated to supply power to the same load of the community under study in this paper. The results indicated that 38,106 kg/year of CO2 was released into the environment, which is a significantly large amount compared to Scenario 2 and Scenario 4, which release only 973 kg/year and 1,327 kg/year, respectively.

It has been observed that the reduced running hours of diesel generators (DG) in hybrid systems not only reduce costs but also significantly lower emission levels. Figure 50 illustrates how hybrid systems can greatly reduce emissions. For example, Scenario 2 and Scenario 4 have reduced CO2 emissions by up to 97% and 96%, respectively, by incorporating DG into hybrid systems, making them more environmentally friendly. In this category, Scenarios 1 and 3 also stand out for their zero emissions. Compared to base case scenario, scenario 2 and 4 which have 97.5 and 96.5 renewable fraction respectively can be considered environmentally friendly.

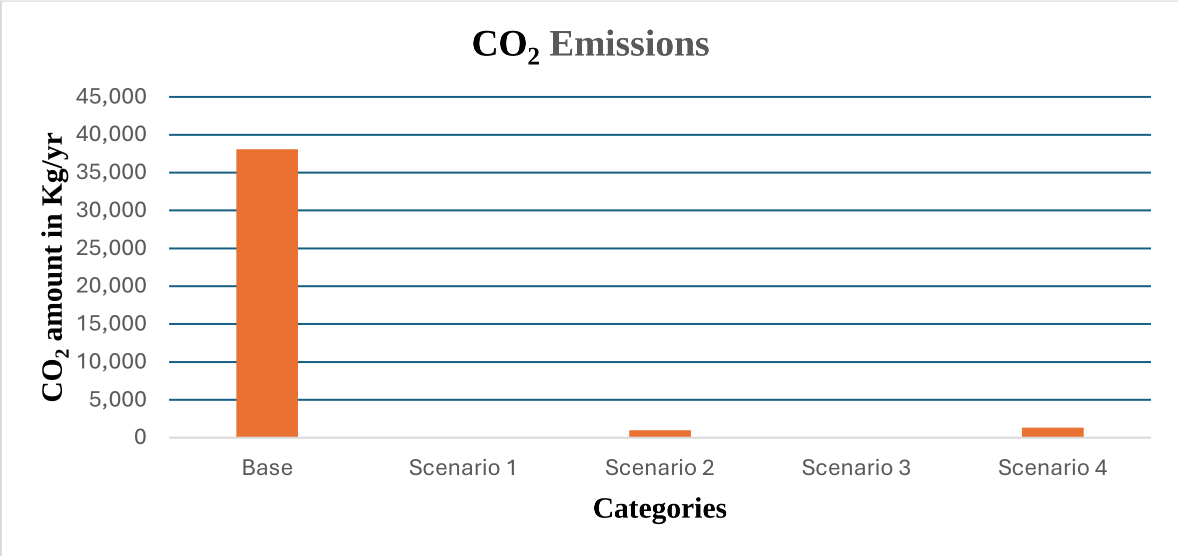

Figure 50: CO2 Emissions

4.4 Evaluating scenarios Strengths and Weaknesses

Table 25 below summary of scenarios weaknesses and Strengths.

Category	Strengths	Weaknesses
Scenario 1	• 100% renewable fraction • Environmentally friendly • Easy to maintain • Backup storage • Low LCOE	• Low energy security as it has 1 generation source • Intermittent power supply • High O&M costs for PV • High expenditure on BESS
Scenario 2	• High energy security, more than one source of generation. • Cheap as in low capital costs • Easy to maintain • Zero excess energy • Low LCOE • Backup storage	• GHG emissions
Scenario 3	• 100% Renewable fraction • Environmentally friendly • High energy security	• Huge capital cost • Highly intermittent making it complex

	• Backup storage	• Higher LCOE
Scenario 4	• High energy security • Zero electricity shortage • Low LCOE	• Hard to maintain • Huge capital cost • High excess energy • GHG emissions

Table 25: Scenarios Strength and Weakness

4.5 Selection of optimal Scenario

Scenario 2 has been selected as best option for Mlangali community for the following reasons.

1. Economic reasons

This is one of main reason scenario number 2 has been selected for this study. The results from simulation of scenario 2 offers low capital cost which estimated at $ 48,000.00 and low Levelised Cost of Energy which estimated at $0.103/kWh which is much lower compared to other scenarios. With these costs the community would have an opportunity to take up the loan and payback on time from the sales generated from the electricity.

2. Power access

Although all scenarios achieved 100% capacity to meet load demand, scenario 2 stood out because it produced the least excess energy amongst the other scenarios making it system with best optimal efficiency.

3. Energy security

Though scenario 4 stood out in this category combining the level of energy security with economic analysis results of the scenarios, scenario 2 gives the best trade off than other systems because it has two generation sources with storage which gives the system the security it requires. The system with more than generation sources are more energy secure because if one generation source failed to meet demand the other can supply in its absence instead of depleting the storage so scenario 2 has at least more than 2 backup system and low capital costs as well as low levelised cost of energy when compared to other scenarios.

4. Emissions

The inclusion of generator makes scenarios 2 and 4 release GHG gasses compared to scenario 1 and 3 which are 100% renewable fraction. Though scenario 2 and 4 release GHG gasses they have best renewable fractions of 97% and 96% respectively which are environmentally friendly systems. The integration of DG in hybrid systems heavily reduces emissions. For example, the scenario 2 reduces emissions by 97.5% which makes it more environmentally friendly. By considering environmental, performance, energy security and economic trade-offs scenario 2 was chosen as the best scenario with very minimal emissions.

4.6 Sensitivity analysis of the chosen Scenario

The sensitivity analysis conducted for the chosen scenario aimed to establish the impact of rising fuel costs on the system, given that Malawi imports fuel, making it susceptible to market fluctuations. Since the selected scenario includes a diesel generator, it is important to understand how fluctuating fuel prices affect the levelized cost of energy (LCOE), CO2 emissions, and capital costs. The analysis involved increasing the fuel price from $1.6 per litre to $2 per litre.

The

Table 26 below shows the prices of the with results obtained from the simulation.

Fuel Price ($/L)	CAPEX ($)	NPC($)	LCOE ($/kWh)	CO2 Kg/yr
1.6	47,644	109,267	0.1032	973
1.7	47,769	109,917	0.1038	944
1.8	47,689	110,620	0.1045	968
1.9	47,689	111,262	0.1051	968
2	47,818	111,195	0.1051	893

Table 26: Fuel Price Sensitivity Analysis Results

The Figure 51 below illustrates the behaviour of system CO_2 emissions when price of fuel increases.

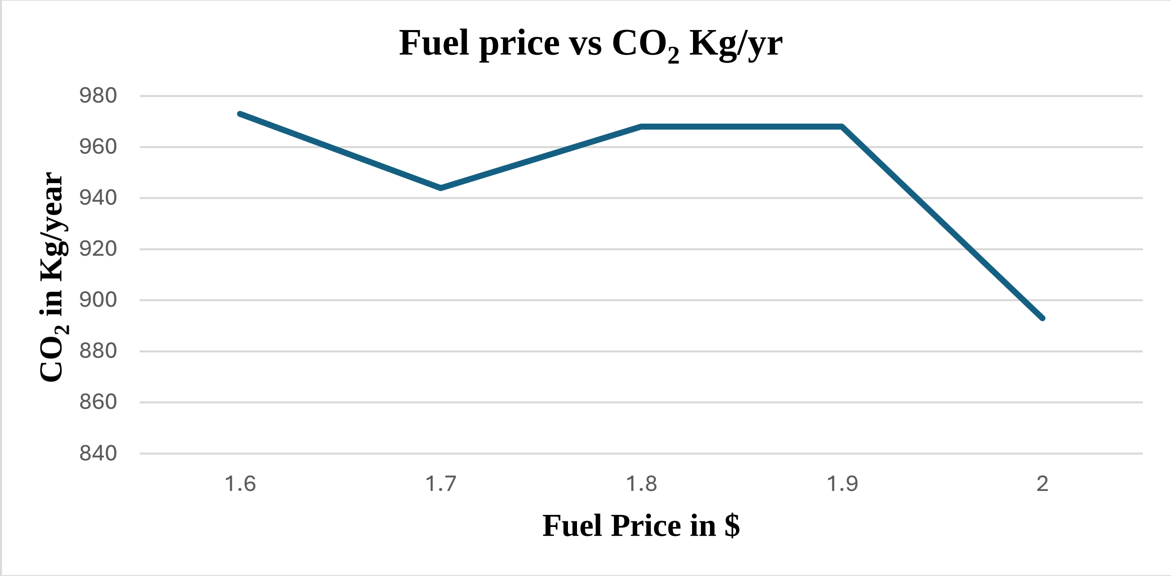

Figure 51: Sensitivity Analysis of Fuel price vs CO_2 Emissions

Although not directly apparent from the plot in Figure 51 it can be observed that increasing fuel prices result in reduced CO_2 emissions. This phenomenon can be explained by the fact that higher fuel costs lead to increased energy costs, prompting the HOMER optimizer to reduce fuel consumption and diesel generator runtimes to achieve the lowest possible cost of electricity. Consequently, as fuel prices rise, the system relies more on renewable energy sources, decreasing fuel usage and, subsequently, lowering emissions.

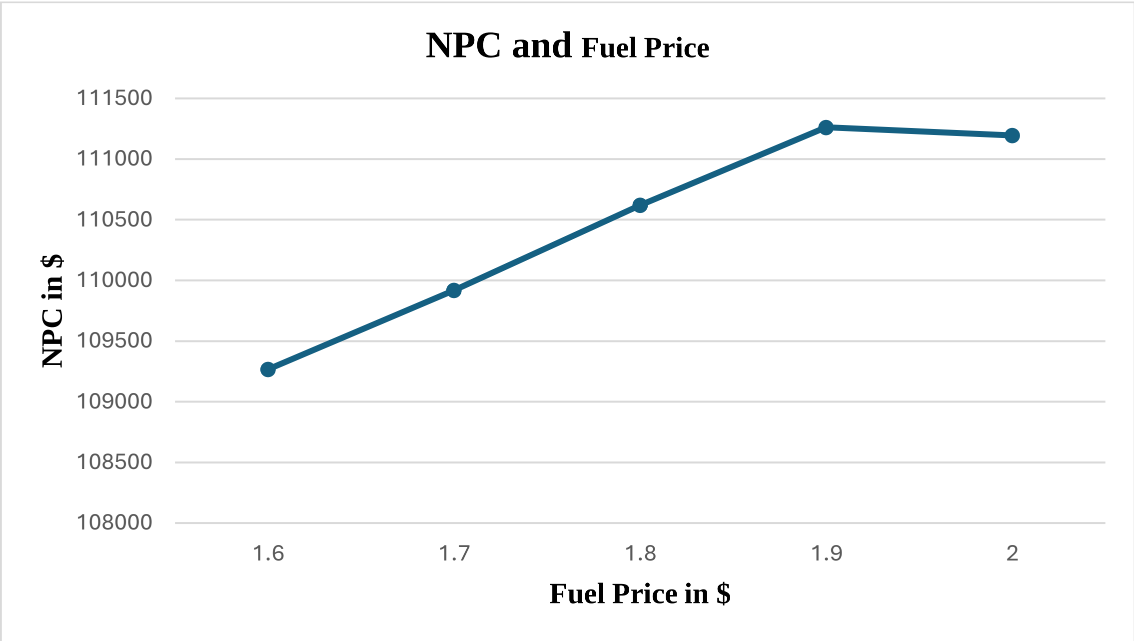

Figure 52: NPC Behaviour as Fuel Price Changes

Another observation is that rising fuel prices lead to an increase in the Levelized Cost of Energy (LCOE). This can be explained by the corresponding rise in the Net Present Cost (NPC) of the system as it can be seen Figure 52 above. As fuel prices increase, the operational costs of the system also rise, contributing to higher overall system costs. These increased costs are important in calculating the NPC, which in turn is used to determine the LCOE. The LCOE reflects the average cost of electricity over the system's lifetime, considering all capital, operational, and maintenance expenses. However, Capital cost does not change that much because primarily there are determined by initial investment on the infrastructure not ongoing costs like NPC.

4.7 Investigating the Changes of Discount constraint on selected System

The discount rate can affect the overall net present cost of the system as well as levelised cost of energy. In HOMER, it is an important financial variable used to calculate future costs and cash flow into its present value. It represents the time value of money, reflecting how much future cash flows are worth in today’s terms. Simulations were carried out for the selected system to determine the effect discount rate applied to the project.

Three discount rates were applied in the study that is 3%, 5% and 8%. The following graphs illustrate the effect of discount rates on the project costs especially net present cost and levelised cost of energy.

Figure 53 below shows the impact of discount rates on capital expenditure and net present cost. It can be seen from the result that high discount rates give low NPC and low discount rates gives higher NPC. Low NPC makes the investment more economical as most of costs are slashed and suitable for short term investments. However low discounts are preferred for long term investments such as renewable energy projects because it favours renewable energy investments and discourages non-renewable generations.

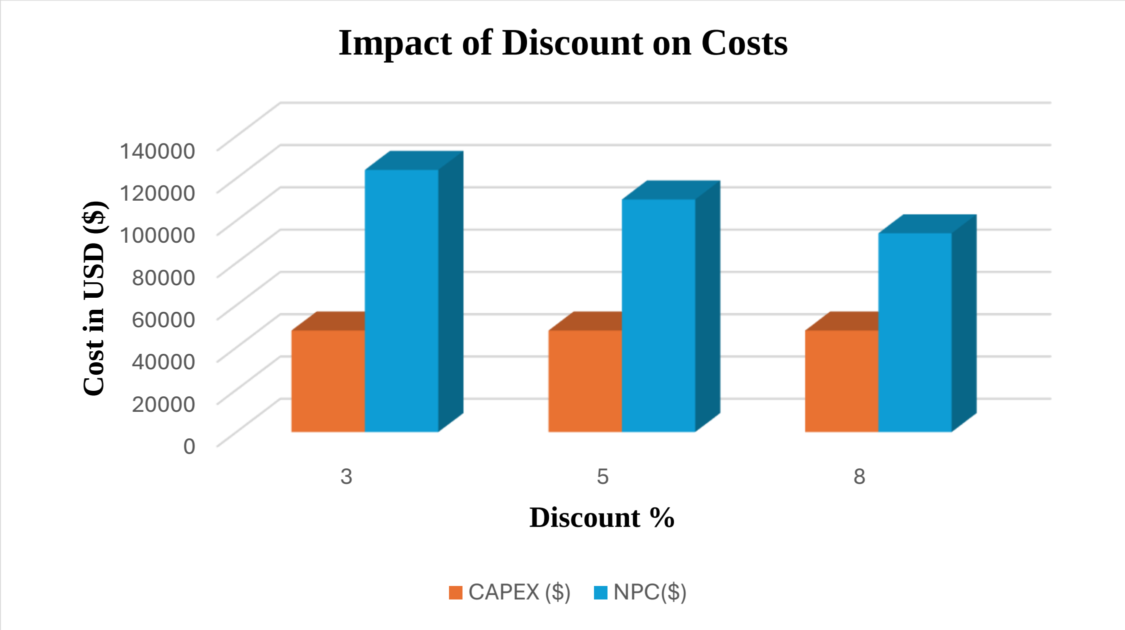

Figure 53: Impact of Discount on Costs

The effect of the discount rate on the Levelized Cost of Energy (LCOE) is significant, as an increase in the discount rate leads to a higher LCOE as seen Figure 54 below. While a higher discount rate results in a lower Net Present Cost (NPC), it is crucial to find a balance between these variables to ensure that optimising one does not unduly sacrifice the other. LCOE is vital for the community because it influences the affordability of electricity for households. Therefore, achieving a balance between profitability and sustainability is essential for the project's success.

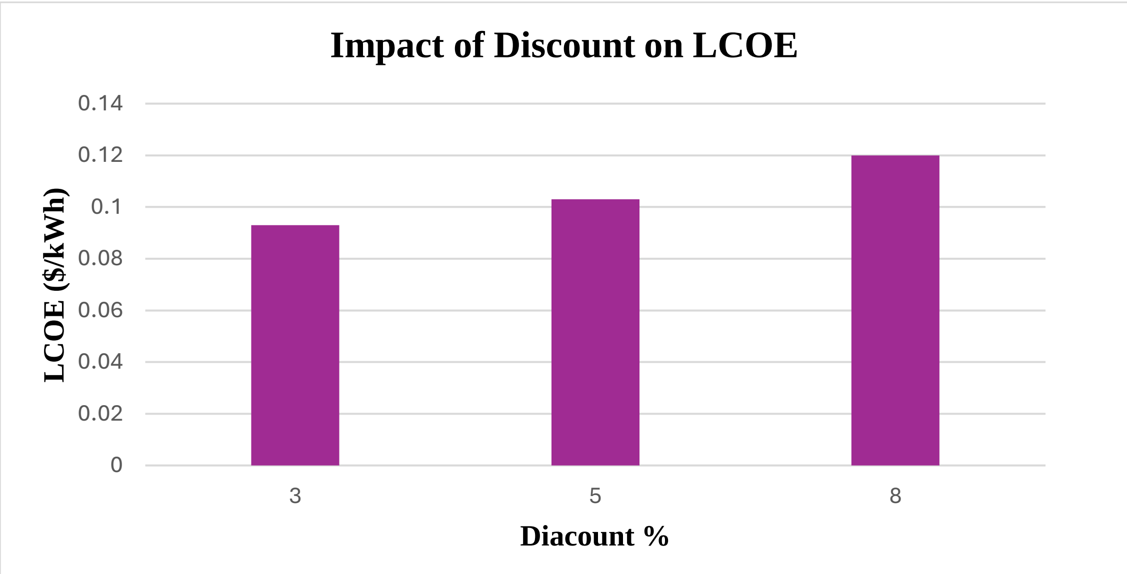

Figure 54: Impact of Discount on LCOE

Figure 55 illustrates the impact of increasing the discount rate on system diesel generator (DG) emissions. In the selected scenario, a higher discount rate leads to increased DG runtimes, resulting in higher carbon dioxide emissions. This occurs because DG-generated power is cost-effective, discouraging investment in renewable energy and favouring cheaper, more polluting energy sources. Which means reduced storage investment to be covered by DG generation in an effort lower cost.

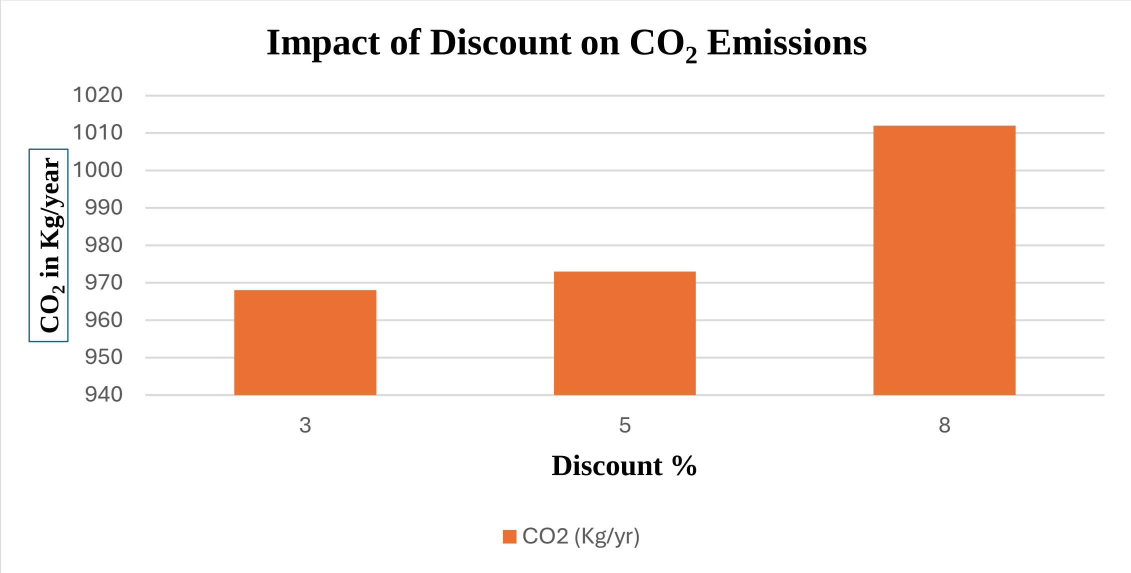

Figure 55: Impact of Discount on CO2 Emissions

Therefore, from the analysis, it is important to find the good balance in discount rate to promote win -win situations that will deliver low cost of energy and environmental conservation.

5.0 FINAL REMARKS

5.1 Conclusion

The project aim was to investigate possible combination of energy generation resources to improve energy access, energy security and focus on clean energy technologies to reduce carbon emissions for communities in Malawi. The found optimal solution is applicable to majority of Malawian communities to supply electricity especially in remote areas. The following are conclusions that can be drawn from the study.

1. Malawi poses numerous electricity generation studies that can be exploited depending on location to improve electrification levels in the countries. The general power source which readily applicable in various locations is the use of solar PV, Battery storage especially for community generation.
2. From proposed scenarios, it was concluded that the combination of solar PV, diesel generator and Battery storage is the best option considering the level of energy

security, economic factors and net reduction in GHG emissions. It was found to have low levelised cost and capital cost more than all proposed scenarios which is crucial for Malawian communities. The inclusion of diesel generator was found to add security and reduce the capital expenditure hence low LCOE and brough some trade-offs with Carbon emission which were deemed necessary considering system reliability, affordability and security.

3. On Emissions of GHG gasses the selected model was found to reduce emissions by 97% from the base model making it more environmentally friendly. Of course, PV battery storage system has 100% renewable penetration but was dropped due to low security.
4. The sensitivity results showed that fuel price changes have no effect on capital expenditure but affect net present cost, levelised cost and level of emissions of greenhouse gasses. Additionally, an investigation into discount constraint revealed that discount rate affects LCOE and NPC such that when making investment a balance must be made to avoid sacrificing one variable for another

5.2 Limitations of this study

Any development project has its own challenges, this study like any other study has its own limitations. The following are some the challenges encountered

1. The load demand profiles used in the analysis were generated based on assumptions, which introduces the risk of underestimating or overestimating the actual demand in the community. This discrepancy could lead to inaccuracies in the system design and performance predictions. To address this issue, it is essential to conduct a comprehensive and detailed study on-site to gather accurate data that reflects the true energy needs of the community.

2. The study assumed that the produced power would all be sold to the community all the time, but this may not necessarily be the case. Comprehensive market Research is needed to understand the market dynamics in the region. By conducting thorough Research, stakeholders can gain insights into potential demand, pricing structures, and consumer behaviour, enabling them to make informed decisions about the project. This understanding is important for ensuring the project's viability and aligning it with the actual needs and economic conditions of the community

3. The lack of official channels and studies to obtain information on similar existing projects in the region poses a significant challenge, as it hinders access to the latest findings and pricing trends. This issue is complicated by the fact that government and statutory corporation websites are not frequently updated, leading to discrepancies with data reported in newspapers. Often, it takes years for such websites to be updated, Resulting in conflicts between official sources and media reports. This inconsistency has impacted the estimation of capital costs and electricity costs in the region, as outdated and inaccurate information can lead to miscalculations and misguided project planning.
4. HOMER database has its own weather data from the selected area of study, but one challenge is that latest data which was registered is from 2013 for region on which the study is based. Ten years is long time climate and weather changes may have changed which necessitates the need for updated resources to get true picture of the region.
5. The HOMER database provides weather data for the selected area of study; however, a significant challenge is that the most recent data available for the region dates to between 2005 - 2013. Given that 10 to 19 years is a considerable long time, climate and weather patterns may have changed, necessitating updated resources to obtain an accurate and current picture of the region. There is need for more recent and accurate data for the region.
6. Homer battery results did not show proper power discharge as in cost cases the battery were rarely discharged.

5.3 Direction for future investigations

Due to project duration, lack of some official information and outdated databases and lack of market research the following are recommended for this Project.

1. **Market Research-** there is need to carry out market research to have fully understand of the project cash flow to make informed decisions and necessary steps to address any discrepancies that exist. This would boost project planning and implementation for successful Project.
2. **Survey-** there is need to carry out community survey to understand their electricity needs and plans as most of the people in the region have never used

electricity in their homes. This would help to model the most realistic initial demand profile and help plan for expansions as demand increases.

3. **Study for more potential renewable energy resources.** There is need to carry out more in-depth study to establish how other renewable energy sources may fit into the system. for example, though wind was not included in selected final scenario doing a study establish its potential would help to find other means of expansion when the project starts to grow.
4. **Sensitivity Analysis.** There is need to do more sensitivity analysis to understand project response to changing dynamics such as inflation, demand, environmental concerns. Demand scaling would help to understand project response to growing demand because the designed system is small but as times goes more houses will need to be connected to electricity so for that reason a study on demand scaling would give an insight on best way to plan the project.
5. HOMER battery optimisation must be investigated as the batteries do not exhibit proper battery discharge. In most scenarios battery was rarely discharged to DoD limit.

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