FEDERAL UNIVERSITY OF ITAJUBÁ

GRADUATE PROGRAM
IN ELECTRICAL ENGINEERING

Integrated Design of Photovoltaic Power Generation Plant with Pumped Hydro Storage System and Agricultural Facilities in Uhuelem-Amoncha African Community

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Master's dissertation submitted to the Graduate Program in Electrical Engineering as part of the requirements for obtaining the Title of Master in Electrical Engineering.

Concentration Area: Electrical Power Systems
Advisor: Antonio Carlos Zambroni de Souza, Ph.D.
Co-advisor: Benedito Donizeti Bonatto, Ph.D.

October 2022
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Author’s Declaration

I hereby declare that I am the sole author of this dissertation. This is a true copy of the dissertation including any required final revisions, as accepted by my examiners.

To the best of my knowledge the design was made with the available information at hand. Future work and/or practical implementation should be preceded by in-depth and integral evaluation.

DEDICATION

This work is dedicated to the Almighty God for making this journey a success.

ACKNOWLEDMENT

I sincerely thank the Almighty God for his grace that helped me to complete this programme despite the challenges. The professional diligence and commitment of my advisors, Professors Antonio Carlos Zambroni de Souza, and Benedito Donizeti Bonatto, were pivotal to the success of this study.

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ABSTRACT

Seasonal and location dependence of renewable energy resources have limited their applications in power generation. Energy storage systems are promising solutions to the intermittence of renewable energy resources. Rural electricity grids are faced with economic sustainability challenges due to low power demand and poverty. As countries hopefully pass through various stages of development, their needs change. The electricity needs of developing countries surely differ from those of developed economies. Most of the global population without access to electricity, and all the consequences of it, is found in developing countries. Energy access is undoubtedly a significant catalyst for development. Developed countries mainly require technologies to ensure energy security, resilience, and occasionally emission control. Therefore, microgrids are emerging technologies capable of supporting the diverse needs of various stages of development. For example, a rural grid design around economic drivers like agriculture and micro industries can mitigate poverty and improve economic sustainability of rural grids. This study presents an Integrated Design of Photovoltaic Power Generation Plant with Pumped Hydro Storage System and Agricultural Facilities in Uhuelem-Amoncha African Community. The design explored the natural availability of water body in an elevated settlement area that offers a natural storage height for hydro energy storage. HOMER (Hybrid Optimization of Multiple Energy Resources) software was deployed to optimize the design.

The designed photovoltaic power generation plant has a nominal capacity of 221 kW. The simulated results show the power supply probability of the plant as 99.9%. The cost of energy (COE) offered by the design is 0.456 [US$/kWh] which is 82% lower than the current cost of energy in the project community based on generation through petrol generators. The System has 100% renewable energy penetration. The plant is designed to power 50 households with a daily domestic energy consumption of 4.46 [kWh] each. The plant capacity also covers the irrigation water requirement of 50 acres of corn farms. A total of 100 units of designed intelligent pest control system will also be powered by the plant. A community refrigeration scheme of 27 [m^3] equivalent volume is part of the plant design load. The benefits from the irrigation, water supply, pest control and refrigeration scheme will enhance the community's socio-economic development and sustain the investment. Quantifying the integral socio-economic and environmental benefits is a subject of a future research.

Keywords: Photovoltaic generation, Pumped hydro energy storage, Agricultural community facility, Energy poverty; Sustainability; Microgrids, HOMER.

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LIST OF ABBREVIATIONS AND ACRONYMS

AS-PSH –	Adjustable Speed Pumped Storage Hydro
COE –	Cost of Energy
DC –	Direct Current
DERs –	Distributed Energy Resources
ESS –	Energy Storage System
HOMER® –	Hybrid Optimization of Multiple Energy Resources
NPC –	Net Present Cost
PAT –	Pump as Turbine
PH –	Pumped Hydro
PHES –	Pumped Hydro Energy Storage
PV –	Photovoltaic
RES –	Renewable Energy Sources
SOC –	State of Charge

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CHAPTER 1 INTRODUCTION

1.1 Background

Energy has evolved with time as a significant economic driver of industrialization and modern way of life in cities and countryside. As a consequence, global energy demand advances jointly with technology. Environmental concerns and sustainability have made renewable energy systems very attractive and ever more feasible solutions for world energy challenges. However, renewable energy sources are known for seasonal and location dependence with the resulting intermittence [1]. Research on suitable solutions to the problems of intermittence associated with renewable energy sources has recognized energy storage systems as a viable solution for growing cases. However, there is no perfect energy storage system as their application is dependent on many factors. Pumped hydro storage, batteries, and fuel cells technologies have been identified as technologically suitable energy storage systems for managing the intermittence characteristics of renewable energy sources [2].

Communities in remote areas are often not supplied by the electric grid. Moreover, the lack of energy and the distance to urban centers mean that the price of candles, diesel, gas, coal, and batteries is much higher than in cities [3]. This feature imposes a severe burden on the inhabitants of these communities. The access to electricity in rural communities is related to people’s standard of living and socioeconomic development. Reference [4] evaluated the role of electricity in improving people’s lives. The study used the capability approach in relating the case of rural electrification in India. The research results show that access to electricity is an essential social amenity that influences people's standard of living. The study, however, noted that the benefits of electricity in the community are not evenly distributed in the sampled families. Access to electricity positively correlated with improved security, recreational activities, adaptation to effects of climate change, and health. The author argued that access to electricity should be used to enhance social and political settings to help the community to transform electricity access to an improved standard of living.

As a result, this study has endeavored to develop an electricity generation design that can be implemented in riverine isolated communities to provide access to electricity. In addition, the design will include an irrigation facility to encourage food production for improved living, thus being compliant with the community’s necessities.

Considering the energy cost in Kenyan households, the work in [5] assessed the impact of solar home systems and energy-related expenditures. A pipeline comparison approach in more than one thousand households showed that access to solar home systems resulted in increased use of LED lamps and reduced use of flame lamps. There was also a reduction in the monthly use of kerosene for lighting. Kerosene deserves special attention since it may be a source of fire and home accidents. In addition, the cost of charging mobile phones was reduced with the cumulative effect of reduced energy cost.

The present study aims to provide an energy alternative to a rural community to address the high energy cost. Electric systems can be considered social-technological systems, as the availability of electricity goes beyond its physical presence in locations. Using electricity improves water consumption, food, health, and education. Therefore, electricity availability in a disconnected community should be the starting point for addressing poverty and social exclusion. Access to electricity is so critical that it is already well regarded as a basic human right.

Renewable Energy Sources (RES) are found in several parts of the world with reasonable cost and can generate sustainable electricity. For this reason, RES penetration level is increasing steadily, and it is often the only energy solution in some regions. However, RES have an undesirable characteristic of intermittence, rendering the use of an energy storage system (ESS) essential. Therefore, the choice of ESS should be made based on storage capacity, available budget, technical characteristics (e.g., lifespan, efficiency), and natural aspects, such as the natural water availability in the Uhuelem-Amoncha community.

According to [6], some factors can contribute to the implementation failure of an electric system in rural areas; the leading factor is the inherent equipment failure in any system. Failures and intermittency in the long term can result in a community lack of interest in the electricity system, which may be a reason for abandonment in the future. Therefore, the proposal for a reliable, robust, and low maintenance system must be considered. Deploying of renewable energy systems with low-cost of storage becomes a preferable solution for accessing electricity in remote communities. Implementing a photovoltaic system combined with the pumping and storage of hydraulic energy involves a significant investment, even in micro hydro-generators. Much of this cost is in the excavation and waterproofing of the reservoirs [7]. Another prominent cost is the pumping system and electro-hydraulic power generation, typically independent devices.

To aim at greater efficiency in potential energy storage, places with natural heights over short horizontal distances will be preferred. An important factor to be considered is the presence of natural lakes or water bodies that can be used as they are or even expanded to maximize energy storage.

In this regard, the proposed design in this study has to do with siting a photovoltaic power generation plant in Uhuelem-Amoncha community with agricultural facilities. This community is located along Enyum river in southeast Nigeria that empties into the Atlantic Ocean. The major occupations of residents are fishing and subsistence crop farming. The electric energy need of the community is principally for lighting, food preservation and charging of mobile phones, The average power rating charger is about 5 (W) [8]. There are about 250 persons in the community with about 50 households and an average of 5 persons per household.

The importance of electricity in rural communities as a major driver of development cannot be overemphasized. Agriculture and rural development can curb rural-urban migration and ensure food security for the ever-increasing human population. Rural-urban migration has been identified as a threat to food security and, in extension, the continuous existence of human life. Rural poverty, food insecurity, lack of employment opportunities, inequality, limited access to social protection and depletion of natural resources due to environmental degradation and climate change are principal causes of rural-urban migration [9], [10]. Sustainable rural development could be a solution to these problems, with long term economic, environmental and social impacts yet to be investigated and supported by public policies around the world.

In most cases, rural communities in developing economies are not connected to the electricity grid. This results in social exclusion and rural poverty. Rural electrification is no doubt a key to inclusive socioeconomic development in developing economies. However, major challenges of regulatory, technical and economic considerations in business-as-usual approaches limit grid extension to rural areas due to low population density and electricity demand along the distance between urban centres and rural communities. This makes microgrid systems better choices in providing electricity to rural communities [11].

On the other hand, agriculture has proven to be the most sustainable source of livelihood for the human population. Agricultural practices in rural communities are major sources of food and raw materials for industrial applications. However, just like any other human endeavour, crop production as an agricultural practice is faced with many prominent challenges, including the menace of rodent and bird pests and lack of food preservation facilities in the rural communities [12], [13]. This research will explore an improvement in [12] to create an intelligent pest control system that will form part of a rural microgrid system capable of improving crop yields in rural farms by effective control of rodent and bird pests.

Food wastage is another drawback to food security and sufficiency, since more than one-third of global food production is wasted. This is certainly a huge problem, since over 850 million people are victims of chronic hunger because of limited access to food [14]. To provide food for the estimated global population of 9 billion people by the year 2050, some drastic changes in food products, ranging from crop management, harvesting, processing and consumption need to be activated. Reducing the quantity of food wasted in the food system is an important approach that can curb the current and future food crisis [15]. This study proposes to minimise food losses from planting to harvesting through effective control of rodent and bird pests and community refrigeration scheme.

This research will integrate pest control and food preservation strategy in a microgrid design for rural agrarian communities to improve food security, social inclusion and overall development in rural communities. The result is expected to provide a blueprint for rural development through energy provision and agricultural schemes.

1.2 Literature Review

As a viable means of providing electricity in rural areas, microgrid systems have attracted the attention of several scholars, companies and governments in recent times. On this note, it is important to define a microgrid system. According to [16], a microgrid system is an integrated energy system consisting of interconnected loads and distributed energy resources, which, as an integrated system can operate in parallel with the grid or an intentional islanded mode. In other words, a microgrid is an electrical network usually made up of small generators, storages, and some localised loads [17]. Microgrid systems allow access to remote applications and exploration of renewable energy resources [18].

Reference [11] made an economic comparison of various microgrid systems with the view to determine the most economically efficient microgrid system for rural electrification in each district of Myanmar at various time periods. The authors studied five microgrid systems namely solar, biogas, solar & diesel, solar & biogas microgrid systems. The results obtained show that hybrid microgrid systems such as solar & diesel and solar & biogas microgrid systems offered more competitive solutions against other single resource microgrid systems studied in the research. The technical and economic feasibility of replacing diesel powered generators with hybrid wind power systems in remote communities was studied by [19]. Eight variations of hybrid wind power systems were studied with their performances in isolated communities of French Islands investigated. Results of the study showed superior economic and environmental performance of the hybrid wind-diesel-battery system over other systems in the study. The wind-diesel-battery system offered the lowest net present cost as well as the lowest cost per kWh. In summary, the study showed that hybrid wind power systems in general are preferred alternatives against diesel generators in French Island and can effectively replace them with justified economic and environmental gains.

Considering the renewable energy potential of Ethiopia and the existing interaction among water, energy and food, [20] formulated a realistic energy demand plan for climatic conditions obtainable in sub-Saharan African agrarian communities. Four different scenarios of microgrid potential functionality and capital cost considering various tolerance levels of scheduled outages. The authors demonstrated the social and environmental benefits of renewable energy based microgrids with the capital cost identified to be sensitive to the introduction of individual or communal machines and appliances. Results from the social impact investigation showed that local communities that have operational machines that could support their agricultural practices would welcome the siting of renewable energy based microgrid systems. The authors also emphasised the need for a pre-implementation education of the local communities to guarantee acceptance and sustainability of a microgrid project.

Energy generation systems are adopting renewable energy systems due to three major reasons of environmental sustainability, exhaustible nature of fossil fuels and economic benefits accruable from renewable generation, microgrid systems are increasingly being adopted as viable options in the exploitation of renewable energy resources for the purpose of energy generation. Energy management in microgrid systems is associated with many advantages ranging from reduced power losses to simplified control processes when compared to energy management in conventional grid networks [17].

As a paradigm shift in conventional rural electrification investments, [21] proposed agricultural driven rural electrification investments in sub-Saharan Africa. They noted that rural financing of electrification remained a challenge and opined that higher private sector investments through innovative business models could be a remedy. The authors proposed using agriculturally oriented businesses to drive electrification projects in rural communities. Results obtained show that the high cost of rural electrification can be made affordable through increased value of locally produced agricultural products. Successes recorded in Rwanda where rural agricultural cooperatives led electrification projects as case study.

Reference [22] acknowledged that energy microgrids operation in rural-off grid and developing communities is still at its early stages of development. Some challenges with the microgrid industry in rural areas include non-uniform government policies, geographic layout, energy availability and local economics. The report recommended that micro-utilities should incorporate some measures such as promotion of energy demand during generation capacity availability, implement demand management strategy to match available generation capacity, improve the capacity of the microgrid to match demand and diversify revenue sources besides electricity like selling other by-products of clean energy generation. International donor agencies are urged to work with national governments to create strategic energy plans for rural agrarian areas, convincing governments on the need for complementary infrastructure such as electricity, roads, water and telecommunication to support agriculture in rural areas. They could also provide microgrid-specific initial market research and agricultural value chain mapping. Finally, they can support rural electrification efforts and improve microgrid viability by enabling agribusiness investments.

Various scholars have provided solutions to the intermittence problem of renewable energy generation. Tilahun [23] proposed a solution to control generation capacity fluctuation due to seasonal water level variations using a pumped hydro storage system for Tana Beles hydropower. The author proposed a pumped storage system with six reversible pumps/turbines. The expected benefits of the pumped storage system will include cost reduction and power availability for peak hour power demand.

Manolakos etal. [24] implemented a stand-alone photovoltaic plant that uses hybrid storage of batteries and pumped hydro storage system in Donoussa Island. The total installed photovoltaic generation capacity was 18 (kW). They used a pump rated 6 (kVA) and a water turbine coupled to a 7.5 (kW) Direct Current (DC) generator. Two identical reservoirs of 150 [m^3] capacity each were used in the lower and upper storage. The daytime energy demand of the village was met through direct supply from the photovoltaic generator using a 25 [kVA], 390 [V], 3-phase inverter. Surplus energy is used to power the pump to fill the upper reservoir. In the night period, water is released from the upper reservoir to drive the turbine for power generation to supply the loads. The battery bank with 100 [AH] capacity supplies primary load peaks. The authors, however, noted that isolated photovoltaic generation plant like this has a high initial cost that may deter investments if there are no other benefits like water supply and irrigation. Hence, the present study will attempt to provide a design that will cater to a community's power generation, water supply, and irrigation, pest control and food preservation needs on a hill along a river.

In a recent development, Obermeyer [25] proposed a cost-effective small-scale adjustable speed pumped storage hydro (AS-PSH) system optimized for the United States energy storage needs. The application was proven through concept design for selected sites with associated costs. The project shows that the proposed technology is commercially viable and can economically serve the energy storage needs of the identified markets with optimal installation opportunities. This report lays credence to the economic applicability of small hydro storage systems in the energy the mix of any country with supporting natural water supplies and storage heights. Uhuelem-Amoncha community has a natural water supply through Enyum river and a natural elevation above sea level that can help the location of pumped hydro storage.

In a bid to establish the economic viability of a pumped hydro storage system, reference [26]investigated the benefits of using pumped-storage hydropower in modern power systems with increasing RES generation in a liberalized energy market. The authors developed a novel operation algorithm that strikes a balance between providing additional capacity to meet peak load and obtaining a justified financial revenue for the high investment cost in a pumped hydro energy storage system. The proposed algorithm was implemented using MATLAB® to analyse the benefits of the Tonstad pumped hydro energy storage system. The results showed that the storage could provide significant revenue in the liberalized electricity market of Norway while reducing fluctuations in the overall system loads.

Reference [27] proposes an optimal design/operation scheme for residential neighborhoods in the context of distributed energy resources (DERs) integration. The overall conclusion is that DERs outperform the conventional grid regarding CO_2 emissions and cost. Reference [28] focuses on irrigation efficiency, which is clearly linked to this paper's proposal of providing reliable irrigation for farming purposes. The proposed scheme in reference [14] is highly effective as it can reduce water demand by up to 54% due to increased efficiency.

Reference [29] focuses more on social aspects as remote villages in Cameroon are assessed. The idea is similar to this work, i.e., to propose hybrid PV/hydro systems. Reference [29] also applies the software HOMER® due to its wide recognition. Despite the similarities, different remote villages inherently lead to distinct results/design specifications. Therefore, publications on the topic contribute concurrently to mitigating energy poverty in several communities worldwide, however this study aims to use agriculture as a driver for the economic sustainability of rural grid through improvement in irrigation, pest control and food preservation.

Reference [30] conducts a thorough literature review on hybrid systems in remote communities; thus, it is critical to understand the trends and characteristics of the proposed solutions. According to [30], more than 90% of studies are conducted in the northern hemisphere, which is a point of concern. Furthermore, more than 60% of studies combine PV and wind power, and batteries are preferred as the energy storage devices in more than 80% of studies. Reference [16]demonstrates that while PH is a promising solution, it is hardly ever proposed since it requires natural water availability and natural elevation. Therefore, it is fair to affirm that the solution proposed in this study takes advantage of natural potential energy and geographical resources on hybrid systems in remote communities. Reference [31] focuses on optimizing hybrid energy systems in Nigeria; however, neither hydro generation nor HOMER® are addressed. Reference [32] argues that wind-diesel–battery systems tend to be superior in the isolated community of French Island (Victoria, Australia). However, as previously mentioned, the feasibility of PH depends on natural water availability. Furthermore, it is widely recognized that diesel generation leads to drastic pollutant environmental impact [33].

Reference [34] focuses on a different approach as hybrid wind, and tidal generation is proposed in a remote community in New Zealand. The main conclusion is that it is possible to decrease CO_2 emissions and NPC based on such design. Reference [35] considers hybrid diesel-PV systems in remote communities in Afghanistan to decrease cost and mitigate energy poverty. Community-based hybrid energy systems are further assessed by Ashok [36] where he opined that hybrid energy system is an excellent solution for rural electrification in remote communities with grid extension challenges and economic drawbacks. Ma et al. [37] proposed a hybrid distributed energy resource (DER) system integrating combined heating and power (CHP), photovoltaic (PV) and wind power as solutions to the electrical and thermal load requirements in community residential buildings. Integration of storage systems in microgrids and conventional distribution systems are viable solutions to the intermittence of renewable generation [38]. Hybrid energy resources of wind and hydro energy have the potential to provide Ireland with energy security at minimal emission level [39].

The potential of microgrids as future power system technologies that will offer distinct economic and environmental benefits was foreseen by [40].There is a need for extensive research and development efforts towards overcoming possible barriers to implementing and deploying microgrids as power system technologies of the future [40], [41]. Reference [42] identified the comparison of microgrid projects in various regions as a criterion that could determine the choice of microgrids in different locations. This implies that some critical concerns and factors should influence the implementation of microgrid projects in any scenario. Rural electrification in developing countries is faced with the challenge of extending grid connections over vast geographical distances. Fortunately, microgrids provide possibilities for integrating renewable energy resources such as solar, wind and other hybrid energy sources as distributed generation schemes in rural isolated communities, just as in the case of Colombia [43]. Energy storage systems are critical components of microgrid systems. Reference [44] studied the feasibility of a renewable energy source generation with a flywheel energy storage system and battery storage system on the Greek island of Naxos. The design explored the deployment of flywheel and battery storage systems to meet the energy demand of households. The HOMER software was used for energy calculations.

Energy access has different implications for different society constituents. To establish the connection between energy access and development, [45] conducted a study in 2009. The results reveal variations in the impact of electricity access on different groups in the community and recommended ethnographic-oriented study methods to capture the comprehensive effect of energy access on development.

As far back as 2010, reference [46] had earlier summarized existing microgrid test systems in North America, Europe and Asia and envisaged their future roles in the evolution of smart grids. The idea of smart grids is currently revolutionizing the electricity industry.

Microgrids have moved from laboratory to commercial deployment. This rapid development is driven by technology advancement, cost reduction, reliability and grid resilience benefits. Other benefits include renewable integration, emission reduction and energy access [47]. Reference [48] reported that a microgrid network with a large community of 7500 homes in Huntlee could deliver a significantly higher level of electricity access than traditional non-renewable energy generation with benefits such as affordability and reliability of energy supply. It concluded that all barriers to energy delivery are surmountable by proper management.

Many countries around the globe are exploring the potential benefits from microgrids implementation targeted at addressing the peculiarities of their economies. China has deployed microgrids to promote local generation and consumption of renewable energy, achieve energy resilience and reduce power transmission losses. Microgrids policies tilt towards optimal capacity development, energy storage technology applications and incentive-based energy markets as major drivers [49]. The growing global environmental concerns on carbon emission and the associated global warming have prompted a continuous quest for solutions aimed at mitigating emission levels around the world. Fortunately, microgrids are flexible power system technologies that support the integration of renewable energy resources in the energy mix [50].

According to [51], adopting distributed energy resources has continued to change the conventional energy distribution grid. Problems associated with the increasing management and operation complexity of the power system can be addressed through the deployment of microgrid technologies. The authors advocate the implementation of microgrids as a solution to the challenges arising from increasing energy demand globally.

Energy access is critical to food and water for human survival. Reference [52] studied the impact of small-scale renewable energy technologies on energy access, water supply and food in rural Colombian communities. Deploying structured interviews, group discussions and observations, it was established that renewable energy systems through microgrids can significantly improve access to water and food across the communities.

The role of microgrids in supporting economic development cannot be over-emphasized. Reference [53] puts the annual losses incurred by U.S. businesses at $27 billion due to power outages arising from aging and outage-prone grid systems. Microgrids systems are taking advantage of these shortcomings in the larger grids to create economic development zones by powering hundreds of businesses through a stable power supply. Microgrids offer resilience, reliability, improved power quality, cost-effective expansion, and growing potential for a reduction in energy cost. An important opportunity provided by microgrids is the ability of site owners to participate in the energy market as ‘’prosumers’’ (energy producers and consumers) through distributed energy resources.

Geographical limitations in Bhutan kingdom made it difficult for grid extension to significant sections of the city, not minding that Bhutan sells electricity to neighboring India. Renewable energy generation options were proposed to power rural and remote communities of Bhutan. The cost of the available alternatives of renewable generation varies with location due to differences in the availability of renewable resources [54]. This is a typical application of microgrids for energy access in remote and rural communities as the most feasible alternative. Developing economies require rapid energy access expansion to encourage production factories' development. In most cases, extending the grids to some parts of the country could be a challenge due to distance and geographical constraints. At this point, microgrids become the most viable alternative.

Recent trends in hybrid microgrids are potential remedies to the problems and solutions arising from increasing world energy demand. Renewable energy integration and energy loss reduction are critical components of the advantages of hybrid microgrids technologies. Solutions to frequency regulation issues, demand response programs and other energy management schemes are compatible with the deployment of hybrid microgrids [55]. Changes in the economic status of various countries influence their purpose of microgrid implementation. These drivers of microgrid projects in developed and developing economies will be x-rayed in the following sections

For a thorough literature review related to the context of this study, the following descriptors were applied to the Scopus database: "homer” AND “hybrid” AND “off-grid". It was verified that Renewable Energy is the leading journal on the topic with 24 high-impact publications, as summarized in Table 1.1. A significant diversity of countries is demonstrated. For better visualization, Figure 1.1, illustrates a map of the publications. This study is the only one out of the 24 that addresses an isolated Nigerian community, which is a country that suffers from energy poverty and deserves greater attention from the research, national and international community. Concerning resources, a significant variety was also verified, with several papers assessing electricity generation from solar, biomass, wind, hydro, and/or diesel, along with battery energy storage. However, none of the 24 papers addressed pumped hydro storage systems (a major focus on batteries is evident). In conclusion, this study focuses on an understudied country and system; thus, it is expected to be of great value for the research, national and international community.

Table 1.1 Summary of related literatures

		Assumed resources ^{a}						
Reference	Country	Solar	Batteries	Biomass/ Biogas/ biodiesel	Wind	Hydro	Diesel	Optimal LCOE [USD/kWh]
Lemence et al. [56]	Philippines	✓	✓				✓	0.54
Ribó-Pérez et al. [57]	Honduras and Zambia	✓	✓	✓				0.06
Lafleur et al. [58]	Canada						✓	No info
Chambon et al. [59]	India	✓	✓	✓			✓	0.18
Odou et al. [60]	Benin	✓	✓			✓	✓	0.207
Atallah et al. [61]	Egypt	✓	✓		✓		✓	0.107
Lozano et al[62]	Philippines	✓	✓				✓	No info
Aziz et al. [63]	Iraq	✓	✓			✓	✓	0.054
Muh et al. [64]	Cameroon	✓	✓		✓	✓	✓	0.443
Haratian et al. [65]	Iran	✓	✓		✓			0.546
Azimoh et al. [66]	Namibia	✓	✓				✓	0.51
Ali et al. [67]	Australia	✓	✓		✓		✓	0.238
Shahzad et al.[68]	Pakistan	✓	✓	✓				0.026
Ramchandran et al. [69]	India	✓	✓	✓				0.23
Mamaghani et al. [70]	Colombia	✓	✓		✓		✓	0.465
Chmiel et al[71]	Scotland	✓	✓		✓	✓	✓	0.238
Bhattacharyya [72]	Bangladesh	✓	✓		✓		✓	0.344
Sen et al. [73]	India	✓	✓	✓	✓	✓		0.42
Kim et al. [74]	South Korea	✓	✓		✓		✓	0.23
Dorji et al. [75]	Bhutan	✓	✓		✓		✓	0.582
Prodromidis et al. [76]	Greece	✓	✓		✓			0.42
Prodromidis et al. [77]	Greece	✓	✓		✓			No info
Nfah et al. [78]	Cameroon	✓	✓	✓		✓		0.352
Nfah et al. [79]	Cameroon	✓	✓			✓	✓	0.296
Average								0.297

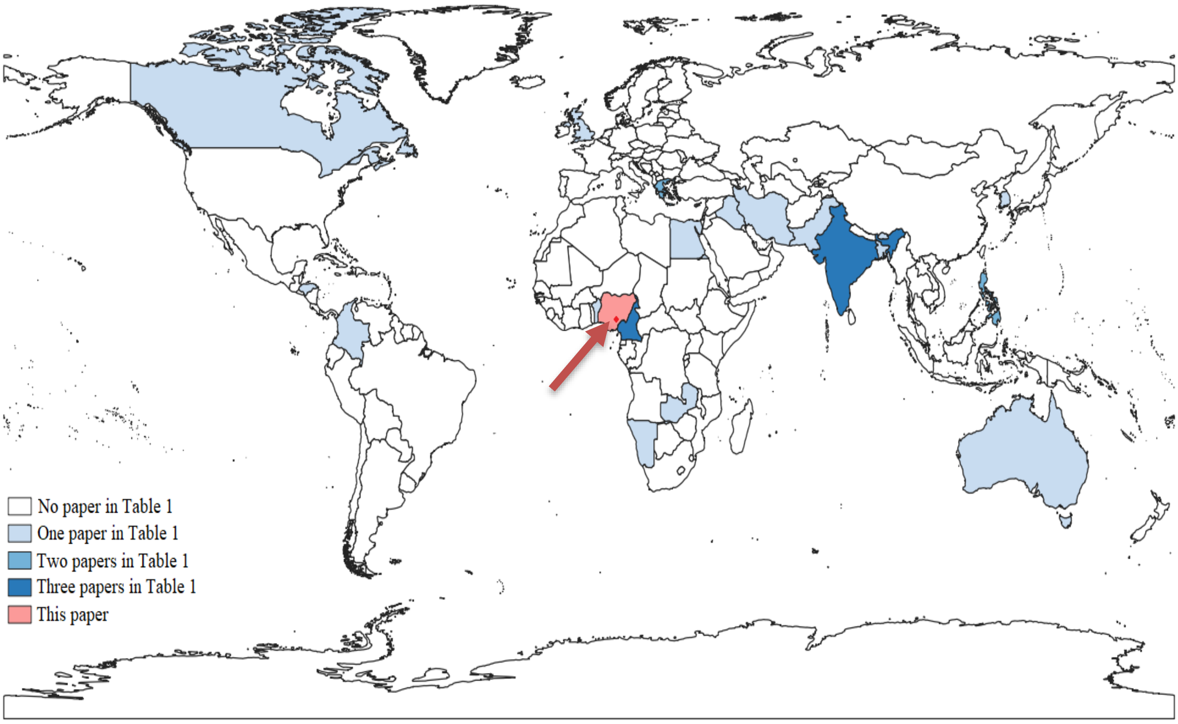

Figure 1.1: Map of high-impact Renewable Energy publications on the topic (exact location addressed in this study is highlighted with a red dot shown by the arrow).

Also, among high-impact publications that are closely related to this study context, stand out: Dumbrava et al. [80] that focus on PV production management and stochastic microgrid optimization. The assumed microgrid is robust with PV generation, thermal engine, ESSs, and critical and interruptible loads. Moreover, it can operate in islanded mode. The goal is to stochastically minimize operation costs, which was achieved by the proposed model. Lazaroiu et al. [63] addressed virtual power plant (VPP) mathematical formulation and implementation. The scheme assumes renewables, ESSs, thermal engines, and demand-response loads, and seeks to maximize the VPP's benefits. The model is implemented based on the GAMS software and results demonstrate that it successfully maximizes benefits.

This study will propose an off-grid pumped hydro energy storage (PHES) powered by a photovoltaic (PV) plant for use in an isolated community. The goal is to design a durable system with low maintenance and ease of operation. The proposed scheme is depicted in Figure 2.1

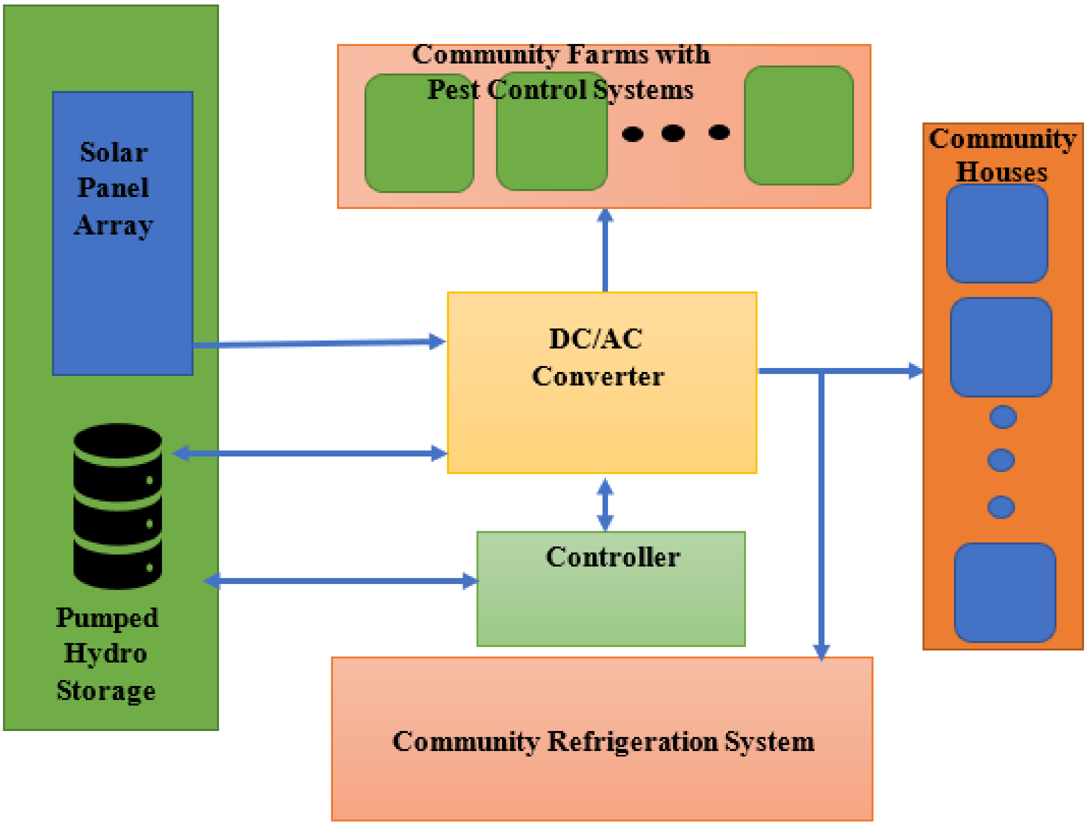

Figure 1.2 Schematic of the components involved in the off-grid hybrid PV-PHES system

1.2.1 Photovoltaic Generation

Solar energy has been identified as the most abundant energy resource on Earth. The amount of energy radiating from the Sun to the Earth matches the energy demand by all species activities on Earth. PV technology is among the major means of harvesting energy from the Sun. Many technological advances are aimed at improving the efficiency of photovoltaic systems. PV technology is a mature and commercially available technology with proven reliability [66]. Due to the environmental sustainability characteristics of PV generation, many nations have made policies to encourage investments in PV generation. This is evident in incentives, subsidies, and tax exemptions granted to investors in PV technologies for certain periods of market maturity and PV penetration into the distribution systems [67].

In a system where photovoltaic solar energy is expected to supply water needs for irrigation and human consumption, the PV plant needs to be oversized so that the generated electricity, under normal conditions, is sufficient to pump and store water to the upper reservoir and supply energy to the homes in the community. Another important point is the quantity of electrical power needed for the houses during the day. To predict the households loads behavior, the HOMER® software was adopted to provide a generation estimate in the proposed model. From the data analysis, an electric system powered by photovoltaic panels was planned. Hence it is expected that the system should be able to supply all the electrical power demand and water pumping as a means of energy storage and community usage at the same time.

1.2.2 Energy storage system

When considering isolated low-income communities, it is necessary to think about a long-lasting, reliable, low-maintenance energy storage system. Battery energy storage systems are the most versatile in electrical conversion. However, they are not feasible in many parts of the world due to cost and sustainability. The same can be said about fuel cells that require special care in fuel storage in addition to their high cost. The option adopted in this research is a hybrid energy storage system of hydraulic storage with minimal battery storage due to some reasons. First, the feasibility of hydro storage is linked to the availability of natural slopes where reservoirs can be created. This premise is of great importance due to the high costs associated with excavating reservoirs [7]. The storage capacity of the reservoirs will meet the community's water needs for human consumption, energy generation, irrigation, and animal use. In this holistic view, the storage system fulfills much more than the energy function but meets the basic human needs that until then were not covered.

1.2.3 Pump as turbine

Pump as turbine (PAT) is not necessarily a new concept, but its use is not yet widespread. Arriaga, in his work [3], proposes that an isolated community can have PAT as an alternative for energy supply. This proposal is interesting due to the good energy quality and cost-effective results for rural electrification, and these facilities can be installed and maintained by the villagers. Indeed, using a pump-type system as a turbine is one of the best solutions that can be applied in remote communities. This topology allows the use of the same hydraulic turbine, electric machine and piping for water pumping and electrical generation, significantly reducing the implementation cost [3].

1.2.4 Community irrigation application

With respect to irrigation application, since the community largely depends on subsistence crop farming for livelihood, incorporating an irrigation facility in the design will enhance food production. In this regard, power generation will be prioritized during renewable energy downtime using stored hydro potential energy. The excess of accumulated water in the storage system will be used for irrigation purposes.

1.2.5 HOMER Energy Software

The acronym HOMER stands for Hybrid Optimization of Multiple Energy Resource. This is a hybrid power system optimization software that can perform complex simulations of hybrid electrical and energy system data and components to determine the least-cost and most effective risk-minimization strategies. The software was originally developed at the US Department of Energy’s National Renewable Energy Laboratory (NREL). HOMER offers a global standard for microgrid optimization. Versions of the HOMER software include HOMER® Pro, HOMER® Grid and HOMER® Front.

HOMER® Pro is a version of HOMER software that simulates engineering and economic feasibility of microgrids or distributed energy systems for off-grid and systems tied to weak grids. The software provides information on costs and energy combination alternatives between conventional and renewable energy, storage, grid resources, and load management.

In a single data run, HOMER$^{®}$ Pro simulates the operation of hybrid microgrid or distributed energy system over a year interval. The results of this simulation include evaluation and optimization of the electrical system design, load profiles, components fuel costs, and environmental variables. Important information from the simulation includes technical performances, risk-mitigation, and projected cost savings.

HOMER$^{®}$ Pro has three powerful tools in a single software package to ensure that engineering designs and economics work together. These tools are simulation, optimization, and sensitivity analysis. The simulation tool simulates all possible combinations of equipment considered to obtain a viable system. Based on the setup, HOMER$^{®}$ Pro may simulate up to hundreds or thousands of systems. The simulation covers the operation of a hybrid microgrid for an entire year period. The optimization tool in HOMER$^{®}$ Pro is able to assess all possible combinations of systems types in a single run and sort the resulting systems according to the optimization variables selected. The optimization tool is able to find the least-cost of combined electrical equipment and resources. With a specified location, electrical load and some cost estimates, HOMER$^{®}$ Pro is able to provide optimization results on the system. The sensitivity analysis tool allows users to know what happens if some variables beyond the control of the designer changes.

HOMER$^{®}$ Cycle Charging is a dispatch strategy that controls a generator to operate at full capacity and uses the surplus power to charge the storage. The controller page provides a setpoint state of charge for the storage device [81].

1.3 Crop Protection for food security

Reference [68] quoted the world food summit to have stated that “food security exists when all people at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. In national perceptive, food security was defined by[83] as the satisfaction of national food consumption needs with certainty. In order to guarantee food security, attention must be given to the various sectors of the food production. Crop production is a very important aspect of the world food chain, because it caters food animal production, food for man and raw materials for industries. Food security can only be sustained if the soil and the environment, which are major components of crop production, are preserved while producing safe food. Agrochemicals have been used for decades as means of enhancing crop yields through crop protection against pests. Pest have in recent times developed resistance to most of the agrochemicals. Also disturbing is the fact that some agrochemicals have been associated with environmental degradation and food contamination. Owing to the need for global food security, efforts must be geared towards increased food production with methods that ensure good food quality and sustainable environment[84].

It is evident that climate change has a stretching effect on the ecosystem, agricultural production, food chains, incomes and trades with pronounced economic impacts on livelihoods, food security and nutrition. Global efforts must be targeted increasing the resilience of food security in the face of climate change through a multifaceted approach ranging from social protection, improved agricultural practices to risk management[82]. The place of new scientific and technological solutions in pest management was emphasized by[85] to reduce current yield losses due to pest and ensure plant health with minimal environmental impact.

Integrated pest management (IPM) aims at effective, economic and safe management of pests through the reduction of their population below a damaging level. IPM has proven to be effective for landscape pests, forestry pests, structural, home and garden pests. IPM reduces the need for chemical pesticides while minimizing and costs and environmental risks. Modern pest control strategies are built around food safety and environmental sustainability.

[12]proposed an environmentally friendly pest control system to check the menace of rodent and bird pests in a farm. The design applies the three basic signals of motion, sound and light deployed by man in scaring rodent and bird pests from the farm. The system uses solar power to drive electric motors, horns and LED lamps to simulate human presence in the farm thus scaring animals away from cultivated farmlands. The design was further deployed in [13] to ascertain its functionality. The results obtained show improved crop yield by averting losses to the tune of 49%.

However, the design in [12], [13] relies on an open loop control system that is time driven. This present research seeks to improve on the design in [12]by introducing an input dependent control system to increase the efficiency of the system and reduce power consumption. In the proposed new design, passive infrared sensors will be deployed to monitor the presence of rodent and bird pests in order to actuate the outputs signals of motion and sound for effective control of pests.

1.4 Community Food Preservation Scheme

Poverty in rural areas of developing countries has made it difficult for individual households to acquire refrigerators for food preservation. [86]identified the lack of electric power supply as a major cause of the poor conditions of rural health care centres in Nigeria and proposed stand-alone renewable energy systems to supply electricity to rural health care facilities for vaccine preservation through refrigerators and to power other medical equipment. The present research plans to explore a community refrigeration scheme to promote food preservation among rural farmers. The scheme is designed to get electric power from the community-based microgrid to power a central refrigerator that would cater for the food preservation needs of the local dwellers that cannot afford personal refrigerators. In this way, food wastages would be addressed as an important means of ensuring food security. It will also help farmers to take good economic advantage of their farm produce instead of selling them at unfavourable prices for fear of spoilage.

1.5 Motivation and Design Objectives

The lack of electric power supply is a serious threat to rural development. Rural farmers lose substantial quantity of food crops to pests. In most cases rural farmers resort to the engagement of school age children to control the damaging effects of bird and rodent pests in the farm. This results in loss of school sessions by the children and also exposes them to adverse weather conditions with the attendant health challenges. Most of the existing pest control measures are either environmentally unfriendly or pose contamination challenges to food[13]. The design proposed in this study is meant to provide electricity using the available renewable energy resources in the community while providing an integrated design for effective control of rodent and bird pests in the farm. Also, the challenge of food storage by rural farmers with no sufficient income to acquire personal refrigerators will be handled by a community refrigeration scheme proposed in this study.

The aim of this work is to provide an integrated design of Photovoltaic Power Generation Plant with Pumped Hydro Storage System and Agricultural Facilities in Uhuelem-Amoncha African Community. This over all aim is to be achieved by implementing the following specific objectives:

a. Assessment of the total electric load demand of Uhuelem-Amoncha community including power required for a community refrigeration facility of 27 [m^3] capacity;

b. Design of an intelligent pest control system;
c. Assessment of the irrigation water need of 50 [acres] of corn farm;
d. Design of Photovoltaic Power Generation Plant with Pumped Hydro Storage System with the required capacity to power the community loads, irrigation facility, pest control and refrigeration system.

1.6 Organization of the Dissertation

The dissertation is organized into five chapters as follows: Chapter 1 presents an overall introduction to the work, Chapter 2 provides a theoretical foundation on microgrid systems, Chapter 3 presents the design methodology, Chapter 4 presents the results and discussion, and finally, Chapter 5 gives the conclusion of the work and its contributions.

CHAPTER 2 THEORETICAL FOUNDATION

2.1 Microgrids

Reference [87] defined a microgrid as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries acting as a single controllable entity with reference to the grid. A microgrid can be connected to the grid while operating in grid-connected mode and could be disconnected from the grid to operate in islanded mode. In addition, [88] advocates a definition of microgrids that would recognise the dynamic nature of the society's needs over time to improve overall system resilience and sustainability.

The major components of microgrids include:

i. Energy Supply System which could be distributed generation such as renewable sources or small combustion turbine;
ii. Energy Storage Systems like batteries, pumped hydro storage, thermal storage and many more;
iii. Demand Response and Efficiency Measures that could minimize overall energy consumption or reduce non-critical loads when operating in isolation;
iv. Energy Management Systems that maintain balance and stabilizes the system through real-time response, predictive and forecasting analysis;
v. Utility Grid Interconnection that provides connection and disconnection to the grid [16].

Microgrids have since been part of the evolution of electric power supply dating from the first Thomas Edison's plant built in 1882 at Manhattan Pearl Street. The trend continued as Edison had built 58 direct current (DC) microgrids by 1886. This scenario shortly gave way to a state-regulated electricity market industry monopoly that resulted in withdrawal of incentives for investments in microgrids. Recent trends in the electricity market have shown that the existing architecture of grid electricity based on top-down unidirectional energy flow is becoming less attractive for sustainable development. As a result, smart grid systems are gaining attention from various governments as a means of sustainable development. A selling point for the microgrid system is its ability to operate as a single, autonomous grid, either in parallel to or islanded from the existing power grid [89].

Based on a recent review on microgrids, [90]classified microgrids according to size, application, operation, distribution system, architecture, distribution configuration, scenario and source as shown in Figure 2.1. Using size as a criterion for classifying microgrids, small scale microgrids are rated below 10 [kW], medium scale ranges from 10 [kW] to 1 [MW], while large scale microgrids are rated greater than 1 [MW]. Considering applications, microgrids could be applied to premium power needs, loss reduction and resilience-oriented applications. Operational modes could also define the class of a microgrid as grid-connected, transitional and standalone operational modes. Microgrids could also be classified according to distribution systems such as DC microgrids, AC microgrids and hybrid microgrids. The architecture of microgrids can also be used as a basis of microgrid classification giving rise to radial grid configuration, ring grid and mech-type configurations. There could also be microgrid classification based on phase distribution configuration namely single-phase, three phase and three-phase plus neutral configurations. Another criterion for microgrid classification is based on scenarios resulting in residential, industrial and commercial microgrids. The primary energy source of a microgrid can also determine the type of microgrids as non-renewable, renewable and hybrid microgrids.

It is important to note that a single microgrid could share more than one characteristic of the identified classes of microgrids, depending on the requirements of the project.

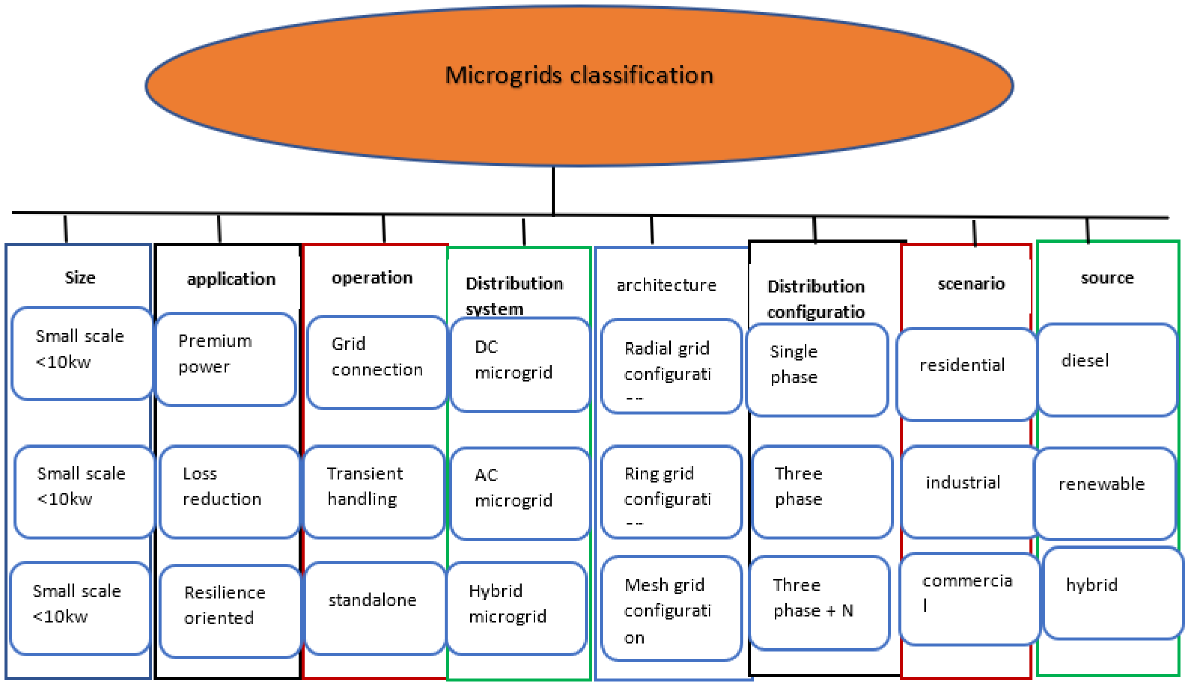

Figure 2.1 Classification of microgrids [90]

2.2 Microgrids in Developed Economies

In recent years, microgrid systems have gained a steady rise in developed economies. The United States of America accounts for close to 34% of global microgrid investments. Microgrid projects could provide energy stability and resilience within project sites or communities if supported by federal and local policies. A review of the state of microgrid investments in the USA shows the need for increased government support through favorable policies, feasibility and technology demonstration projects, and improved research on distributed energy resources and technologies. There is also the need to define microgrid investments' social and economic benefits in each demonstration project to encourage investments in microgrid projects [91].

Implementing microgrid projects in developed countries with existing electricity could reduce greenhouse emissions using renewable energy resources as primary energy sources. Another eminent gain of deploying microgrids in developed economies is the rapid recovery of the power system from climate-triggered disturbances and collapse.

Existing literature shows a major concentration of community microgrid projects in the USA, EU, Asia, and Australia. It was observed that investments in microgrid projects are influenced by formal and informal sectors of the economy. As a major stakeholder in microgrid investments, power utility companies are influenced by formal and informal sectors to improve on their conventional business models. There is a need for regulatory updates on the implementation of microgrid projects. Considering the aging electricity grid infrastructure in the USA, investments in community microgrid projects could be a means of improving resilience and stability in electric power supply. The USA, through federal and state authorities, provides enabling policies to encourage community microgrid programs. For the EU, the local communities are the major drivers of community microgrid projects. Advanced technical and market feasibility research on microgrid investments is done through EU research programs. On the other hand, community microgrid investments in Asia are driven by increasing demands for electricity by fast-growing megacities expansion. There is also growing competitiveness for local investors in microgrid projects in Asia. As for Australia, the demand for energy self-sufficiency by consumers and the resulting decrease in their dependence on the grid is the major driver of community microgrid programs [92].

Energy security, economic benefits, and clean energy integration have been identified as major motivations for microgrid investments in developed economies. Microgrid systems have the potential to improve the resiliency and reliability of electric power supply in developed countries and, as such, ensure energy security. The cost of maintaining and expanding power infrastructure in developed economies has grown with an increase in generation capacity. Microgrids offer alternatives for the expansion of transmission systems and, as such, reduce the cost of infrastructure replacement. Fuel-saving is also a huge economic gain derivable from deploying microgrids in developed countries as microgrids are amenable to renewable energy fuels that are naturally available and unexhaustive in nature. The rising spate of climate change in the face of increasing energy demands also makes microgrid systems attractive solutions in developed economies. This is because of the need to integrate clean energy sources into developed countries' energy mix to curb global warming [93].

2.2.1 Typical Microgrid Projects in Developed Economies

In this section, some examples of microgrid projects in developed economies are presented with emphasis on their locations, profiles, the purpose of deployment, solutions, and expected results.

Table 2.1: Summary of some typical microgrid projects in developed economy

ID	Project	Location	Profile	Purpose/Expected results	Solutions
A.	Marine Corps Air Station Miramar Mission-Critical Microgrid [94].	San Diego, California, USA	The microgrid covers 3500-acre Marine Corps Air Station Miramar operation and maintenance facility	Microgrids for Improved Security Due to compromise or damages to air station critical facilities require uninterrupted power supply irrespective of grid power status.	The station uses existing energy resources such as landfilled gas and solar PV combined with a 7 MW generation plant.
B.	Oncor Campus Microgrid [94].	Lancaster Texas USA	100 + acre system operating facility	Microgrid for Energy Resilience	The Oncor innovative system consists of four interconnected microgrids using nine different distributed energy resources. The resources include inverter and non-inverter-based resources.
C.	Horizon Power Microgrid, Onslow, WA [95]	Onslow is a remote coastal town 1,150 km north of Perth, Western Australia	Microgrid controller and Distributed Energy Resource Management System (DERMS)	Renewable Energy for Emission Reduction and Environmental Protection	Horizon Power set out to integrate multiple renewable energy sources and batteries with existing infrastructure in a controlled microgrid.
D.	Western Power, Kalbarri Microgrid, WA [95]	Kalbarri is a coastal town 570 km north of Perth, Western Australia, with an indigenous population close to 10,000.	The West Power, Kalbarri Microgrid, WA is a remote residential & commercial microgrid	Demand Fluctuation Management	There was an integration of residential rooftop PV with wind and battery storage to create a connected microgrid.
E.	Fort Chipewyan Solar Microgrid [96].	The solar microgrid is located at Fort Chipewyan, about 200 kilometers north of Alberta’s oil sands	It is a 2.2 MW solar farm combined with a 600 kW solar owned by ATCO with a battery storage system.	Emission Reduction	Deployment of solar PV technology in combination with a battery storage system was used to achieve power stability.

The challenges of smart cities require that engineers as major stakeholders in smart city designs must consider sustainability and social inclusion as critical aspects of designs. The people should be the major focus of any engineering project as they are the end-users. Merging engineering with social inclusion is a paradigm that could ensure a world of close equality. Hence, the philosophical trend that opines that technology is not neutral should be given a broader view. The crime trigger aspect of the 1977 New York blackout emphasizes the connection between social orderliness and electricity. New York was plunged into darkness, resulting in riots, looting, fire outbreak, and other violent crimes. The cause of the blackout was traced to both technical and human failures.

The application of microgrids and smart grids for energy access in developing economies and emission reduction and energy resilience in developed economies, respectively, is a typical holistic approach to using engineering to solve societal problems. A holistic smart grid is one that, in addition to technical design, considers social inequalities, social justice, social inclusion, human rights, and sustainability [97].

Energy access drives microgrid investment in remote and isolated communities worldwide. Secondary concerns of sustainability and environmental preservation make the exploration of renewable generation a vital component of microgrid systems. Reference [98] has observed that the deployment of microgrids in states across the United States of America shows that states with high occurrences of disasters and more needs for resilience are more likely to embrace microgrids as microgrids are potential solutions to resilience concerns.

2.2.2 Energy Democracy

The advent of the smart microgrid power system has redefined a new era of power system market relationship between the once complete consumer, now "prosumer" and the utility provider. At first, one may think that the relationship between engineering/technology and philosophy has minimal consequences. However, with the current dynamic realities of the effects of technology and engineering products on society, one cannot afford to isolate engineering/technology from philosophy and ethics if the world must explore the gains in modern technological advancements with minimal catastrophe. In this sense, if adequately applied in engineering/technology designs, philosophy and ethics could make the world safer and more sustainable, but taking the science of reason and morality away from technology would spell doom for the world.

Advances in technology and engineering designs have resulted in severe alienation of engineers from society and the realities of the effects of technology on society. In power systems, for instance, there are numerous gains associated with the advent of smart grids in the power system topology.

These gains include an increase in reliability as local sources could supply system loads in times of grid failure. Energy consumers could become energy producers, sometimes giving rise to the term "prosumers" describing consumers acting as producers during some periods of the day. Plug-in-hybrid electric vehicles could reduce emission-related pollution, thus making renewable energy generation a key player in environmental preservation and protection.

On the contrary, the cost associated with telecommunication and system control facilities could challenge smart grid integration. Utility companies could also oppose the idea of smart grids as they could reduce their total profits, since consumers could become prosumers using renewable energy generation. Utility companies are responsible for maintaining the system's overall reliability and stability, considering the possibility of insufficiency on the part of the microgrids[99].

Energy democracy is an emerging concept propelled by recent advances in smart homes and increasing decentralization of smart grids. The rising implementation of renewable generation and energy storage systems in smart homes has led to more decentralization and democratization of the energy supply system [100]. This means that at a certain time of the day, the energy consumer can change to an energy producer and sell the excess of the produced energy to the utility company. Energy consumption and production is no longer unidirectional with the advent of smart grids and smart homes. Reference [101], as a part of demand side management program, energy democracy has become a very important concept and policy aimed at increasing customer participation in energy management schemes through smart grids. The role of energy prosumers in modern power systems is an important paradigm shift that has changed how energy is produced, utilized and exchanged as a resource. The term prosumer dates to 1970’s when economic-oriented microgeneration, emission control and concerns over the depletion of fossil fuel reserves were principal considerations. The USA, UK and EU were at the forefront of this revolution. Recent advances in Internet of Things (IoT) have continued to improve the concept of energy democracy through smart grids [102].

Geographical terrain is another major factor in choosing a microgrid in some developed economies outside the quest for resilience in electricity supply. Challenges posed by environmental constrains make microgrids attractive alternatives for energy access. As a developed economy, Canada has 291 remote communities of about 195,000 people. Out of these communities, 170 communities are indigenous communities with a population of about 130,000 people. Most communities are inaccessible by road during different seasons of the year [103]. These terrains make it difficult for a continuous grid to reach. Microgrids are the most feasible means of providing electricity to isolated communities. However, this comes with its peculiar challenges. In the case of northern Canada, electrification of remote communities is faced with numerous problems ranging from dependence on fossil fuel, high electricity rates due to transportation costs, and inaccessibility of bulk electricity. Other issues include increased greenhouse gas emissions and low system flexibility and reliability. Microgrid technology can reduce the challenges by using hybrid renewable generation and storage systems [104]. Okoromah [105] has identified residential and remote microgrids to have the highest market potential in Canada. This cannot be isolated from the nature of the remote communities in terms of accessibility with bulk power system investments.

The challenges of smart cities require that engineers as major stakeholders in smart city designs must consider sustainability and social inclusion as critical aspects of designs. The people should be the major focus of any engineering project as they are the end-users. Merging engineering with social inclusion is a paradigm that could ensure a world of close equality. Hence, the philosophical trend that opines that technology is not neutral should be given a broader view. The crime trigger aspect of the 1977 New York blackout emphasizes the connection between social orderliness and electricity. New York was plunged into darkness, resulting in riots, looting, fire outbreak, and other violent crimes. The cause of the blackout was traced to both technical and human failures.

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2.3 Microgrids in Developing Economies

Energy demands in developing economies are rapidly increasing because of growing industries and investments. Developing countries are more concerned with the target of meeting the ever-growing energy demand of the economy.

According to [106] access to electricity in Indian rural communities is faced with some challenges, despite India's aggressive grid extension campaign. These challenges are associated with financial disincentives due to subsidized tariffs and low payment willingness among rural low-income consumers. The authors recommended using super-efficient appliances to mitigate the problems of financial disincentives identified. This, they argued, could reduce the cost of energy consumption for rural households by over 70%. Considering these constraints and the need to use energy access to drive development in developing economies, it is important to encourage productive energy use in rural areas, the major sources of food and raw materials in developing countries.

Microgrids and renewable energy systems provide easier financing options for the energy needs of developing economies where financial resources are very scarce for major grid investments [95]. In most cases, developing countries have some communities that are yet to be connected to the grid due distance and resources required to extend the grid to remote communities. In this scenario, microgrids present viable alternatives for energy access.

In a world of unequal resource distribution, [107] advocates a common property resource approach to electricity access in rural communities of developing countries. He states that extending the common property resources ownership to community microgrids, as in the cases of water for irrigation and pasture for animal breeding, could help the economic drive for rural electrification.

Rural electrification can contribute to rural development by promoting social and economic activities in rural areas. A case study of a community-based electric micro-grid in a rural Kenyan community shows that access to electricity improved the use of electric equipment and tools by small and micro enterprises and increased their productivity between 100 to 200% while resulting in income growth of 20–70%. There were also significant improvements in the social, welfare, and business services like schools, water supply markets, and agriculture. The overall economic effect was the ability of the rural dwellers to make enough to pay for the electricity they use in a sustained manner [108].

Based on the results obtained from previous deployments of microgrid systems in developing economies, microgrids could be agents of development if adequately managed in rural areas of developing countries. In this regard, microgrid investment can be tailored to fit into the economic needs of any community using the most optimal available resources.

2.3.1 Market Incentives and Drivers of Microgrids in Developing Economies

Unlike in developed countries, where investments in microgrids are majorly driven by the quest for energy resilience, reliability, security and emission control, microgrid investments in developing economies are mainly encouraged by the increasing need for energy access for economic developments.

Over one billion people in developing and underdeveloped countries have no access to electricity. In most cases, rural dwellers are the major victims of energy poverty and deprivation. The rural population constitutes a vital sector of any developing economy due to their role in agriculture for food and raw materials [109]. Rural communities need every comfort to sustain food and raw material production to advance the economic fortunes of developing countries. Neglect of rural areas by government and investors has resulted in rural-urban migration with the consequences of reduced human resources for agriculture which is a primary source of raw materials.

Developing countries are countries in transition from underdevelopment to development, the ability of developing countries to effectively attain development within a specified time is related to the pace at which the overall country is developing in all critical infrastructure areas. Energy access is a critical determinant of development. This is because industrialization is largely driven by access to energy. In most cases, rural communities are left out of development plans in developing economies. The case of Brazil with rapid development strides and an underdeveloped Amazon region is a typical example of the nature of developments in developing economies. Reference [110] worked on a design for the possible electrification of remote communities in the state of Amazonas with renewable energy-based microgrids as an option. Load profile and resource data from the location in a HOMER simulation showed that hybrid renewable energy resources like solar and hydro could offer a sustainable source of electricity supply to the isolated regions.

Indonesia, as a developing economy, has achieved an electrification ratio of 99.2% as of 2020. The slow pace of electrification experienced by the country since 2018 is associated with the unfavorable characteristics of the remaining regions against the deployment and sustainability of microgrids. The challenges identified in these areas range from land ownership, social engagement problems, availability of preliminary surveys, technical and practical knowledge issues, and operation and maintenance challenges [111]. The authors proposed a framework that mitigates these challenges by making the challenges visible at each phase of the microgrid development and enabling stakeholders to deploy matching strategies against each challenge.

The African Union (AU), as a continental body of 55 African countries, has recognized the challenge of access to energy as a threat to rapid and even development in the continent on a global and continental scale through the Sustainable Development Goals (SDGs) and the AU Agenda 2063 respectively. While Goal 7 of the SDGs targets universal access to affordable, reliable, sustainable, and modern energy by 2030, the AU Agenda 2063 aims at a 50% increase in electricity generation, 50% distribution, and 70% of Africans with access to electricity by 2023. With the increasing need for energy in Africa, there is a need to adapt Microgrids in the African context considering factors like site selection based on primary energy resource availability, load profile, the demand and willingness to pay, and the expected return from each project [112]. If the sustainable development goal of universal energy access must be achieved, attention must be given to remote rural communities; microgrids technologies are viable alternatives for achieving universal energy access considering the resource and environmental limitations of the conventional grids.

The role of microgrids in salvaging African communities from the challenges of development was emphasized by [113], while they noted that productive use of energy is vital to microgrid sustainability in rural communities. The productive use of energy in rural microgrid have financial and social dimensions. The financial aspect of the design considers an optimal system to accommodate the energy requirements of productive energy users like small businesses. Poor demand forecast has led to oversizing in most existing microgrids in Africa. There is a need to ensure appropriate sizing during the design phase to guarantee the sustainability of the project. Social impacts of microgrids in rural African communities include job creation and its economic spiral effects, environmental preservation through renewable generation mix, and gender equality through employment and reduced crime rates. In the next section, typical microgrids in developing economies will be discussed.

2.3.2 Typical Microgrid Projects in Developing Economies

Autonomous renewable energy microgrids deployment in Africa would be efficient in rural applications due to the long-distance separation of rural communities from the central grid and the resulting high cost of extending power from the central grid. Also, rural communities present low load demand and, as such, can be conveniently supplied from optimally designed microgrids with renewable generation and storage systems [114].

The Nigerian economy is dubbed the largest in sub-Saharan Africa, with a GDP of about \$448billion. Nigeria also has the largest population in the African continent with 200 million people. Irrespective of Nigeria's soaring population and economic potential, the country has only a 60% rate of electrification. Electricity demands in Nigeria have continued to grow rapidly as the country trails behind other comparable sub-Saharan African countries like Ghana, which has 83% electrification rates, and Kenya, also higher at 64% [115]. Microgrid alternatives could play an important role in filling the growing electrification gap in Nigeria and other world developing countries. Several rural electrification projects have been carried out by the Rural Electrification Agency of Nigeria, exploring the solar energy potentials of the country [116]. There is a need to diversify the country's energy mix through versatile energy storage systems and renewable energy generation.

Table 2.2: **Some typical microgrid projects in developing countries** [116]

ID	Project	Location	Profile	Purpose/Expected results	Solutions
A.	Eka Awoke Mini-grid	Eka Awoke community in Ikwo Local Government Area of Ebonyi state is a rural community in Nigeria	The project is an off-grid 100kW solar hybrid mini-grid power plant	Energy Access Homes, businesses, and the entire community would have access to clean, safe, and sustainable energy.	Deployment of solar PV technology and a diesel generator with a battery storage system was adopted
B.	Adebeyo Community Solar hybrid mini grid	Adebeyo community in Ovia South Local Government Area of Edo state is a rural community in Nigeria that had been without electricity for 60 years before the installation of the project in February 2021	The project is an off-grid 100kWp solar hybrid mini-grid power plant	Energy Access Homes, businesses, and the entire community would have access to clean, safe, and sustainable energy	Deployment of solar PV technology and a diesel generator with a battery storage system was adopted
C.	Solar mini-grid Dakkiti Community	Dakkiti community in Akko Local Government Area of Gombe state is a rural community in Nigeria	The project is an off-grid 85 kW solar hybrid mini-grid power plant.	Energy Access Five hundred households in the community would have access to clean, safe, and sustainable energy.	Deployment of solar PV technology and a diesel generator with a battery storage system was adopted

Rural microgrids can improve rural economic development. For example,[117] observed that rural domestic and small business consumers experienced increased economic activities by deploying a wind-power mini-grid project to local tea factories as a demand anchor in Kenya.

About half of the global population without access to electricity live in Africa. The rural population in Africa accounts for the majority of Africans without electricity access. Deployment of photovoltaic generation has been explored as a viable means of electrifying rural communities. Two different off-grid solar PV projects in Kenya were studied. The projects were Sidonge A and Solar Home Systems (SHS) in rural communities around Bungoma/Kitale to assess the impact of access to electricity in the communities. Results obtained from the study reveal positive impacts on rural health, education, security, and access to communication through mobile phones. Microgrids offered greater business support than SHS, whereas SHS was a cheaper alternative [118]. This supports the basis for exploring the benefits of microgrids in developing economies. The social impact of microgrid deployment in developing economies could be a catalyst for sustainable and inclusive development.

According to [119], Brazil has an estimated 2 million families yet to be connected to the national grid. A significant number of families in this condition are located in villages with the least possibility of national grid connection due to their remote locations. The authors proposed a standalone microgrid with hybrid wind-solar generation to encourage productive use of energy in rural Lençóis Island.

2.3.3 Microgrid Systems as Potential Drivers of Agricultural Investments in Developing Economies

Processes in modern agricultural practices are energy-intensive. Cultivation, crop protection, food processing, packaging, and storage require enormous electricity supply, unlike crude agricultural practices that depend on manual labor. Continuous dependence on fossil fuels to provide energy for agriculture in developing countries contributes to increasing global warming. Applying renewable energy resources such as solar, wind, pumped hydro storage, and other renewable energy resources in agricultural activities will reduce climate change. Developed countries have well-adapted renewable energy applications for agriculture, while developing countries are yet to fully embrace renewable energy resources in powering agriculture due to technical and economic drawbacks[120]. The potential applications of renewable energy in agriculture in developing economies can be fully explored through the deployment of rural microgrids in agrarian communities. This will encourage productive use of energy and, in turn, improve the economy of rural dwellers with spillover effects on the national and global economy. The chain of economic activities associated with agriculture can support rural microgrid investments and improve social inclusion.

2.4 Social Inclusion in Electrical Grids Design

To make a real social inclusion, at least, two things must be considered. The first one is the people’s behavior within their environment, considering physical and cultural aspects. Then, secondly, the local economic and financial aspect should be assessed.

2.4.1 Location and Population Economic Considerations in Rural Grid Designs

The term rural refers to a very diverse group of areas associated with a common characteristic from the peri-urban to the very remote communities. Poverty levels are higher in rural area as against urban areas. The rural areas are homes for the extremely poor population in Sub-Saharan Africa and

Amazon region in which more than half of the rural population live in extreme poverty. The World Bank puts $1.90 daily income per person as the international poverty line for extreme poverty [121], [122].

Most rural communities in developing economies have poor road networks resulting their inability to access urban centers for transaction purposes. It is estimated that close to one third of the world rural dwellers do not have access to paved roads. This directly limits their economic opportunities. A study on the relationship between rural road infrastructure and development revealed that good access roads to rural areas have direct impact on the prices of goods and services, availability of non-local goods, improved use of agricultural technologies, productive engagement of the youth population and improved school enrollment for school age children [123].

Unfortunately, rural communities in many developing economies do not have access to good roads. Apart from access roads, electrical grids deployment in rural areas can drive economic development through productive use of electricity. The major source of livelihood in rural areas is agriculture, therefore, electricity can be useful to improve agricultural investments by driving food storage, processing, and packaging.

Considering the potentials of microgrid and nano grid systems to address the problem of energy access in rural communities for the purpose of reaching the United Nations goal of Sustainable Energy for All – SE4All), investment attentions are increasingly shifting to the deployment of these technologies. However, some challenges that border on sustainability of the systems include regulatory concerns, low energy demands in rural communities, low payment compliance rates and over-sized demand design projections [124]. Any rural microgrid design that can address these identified challenges could offer a sustainable and social inclusive rural electricity access.

2.5 Chapter Summary

As countries pass through various stages of development, their needs change. The electricity needs of developing countries differ from those of developed economies. Most of the global population without access to electricity is found in developing countries. Energy access is a significant catalyst for development. Developed countries require technologies to ensure energy security, resilience, and emission control. Fortunately, microgrid technologies can take care of the identified interests in developed and developing economies. For a world of equity and inclusion, microgrids are viable energy system designs that can be adapted to serve the various needs of all levels of the economy. They are not limited by topography, hydrology, and distance, as in the case of conventional grids. They are flexible enough to serve any desired interest. Therefore, microgrids may work as technological and social drivers of changes in countries of different economic profiles. What it is missing to mainly provide the human rights and sustainably reduce energy poverty is political power and willingness to create the laws and business incentives to make it happen, since financial analysis will easily prove the viability of the endeavours, both in developed or developing countries.

CHAPTER 3 METHODOLOGY

3.1 Methodology

To carry out the dimensioning of the hybrid photovoltaic-hydraulic system, it is necessary to know precisely the loads connected to the electric microgrid and the amount of water used in agriculture so that the community does not lack water or energy. This information is valuable because it will also serve as input to the HOMER® program to help the system simulation determine which specifications will be the most viable. Assessment of community needs is pivotal to the design of any community project. The methodology adopted in this study is summarised in Figure 3.1.

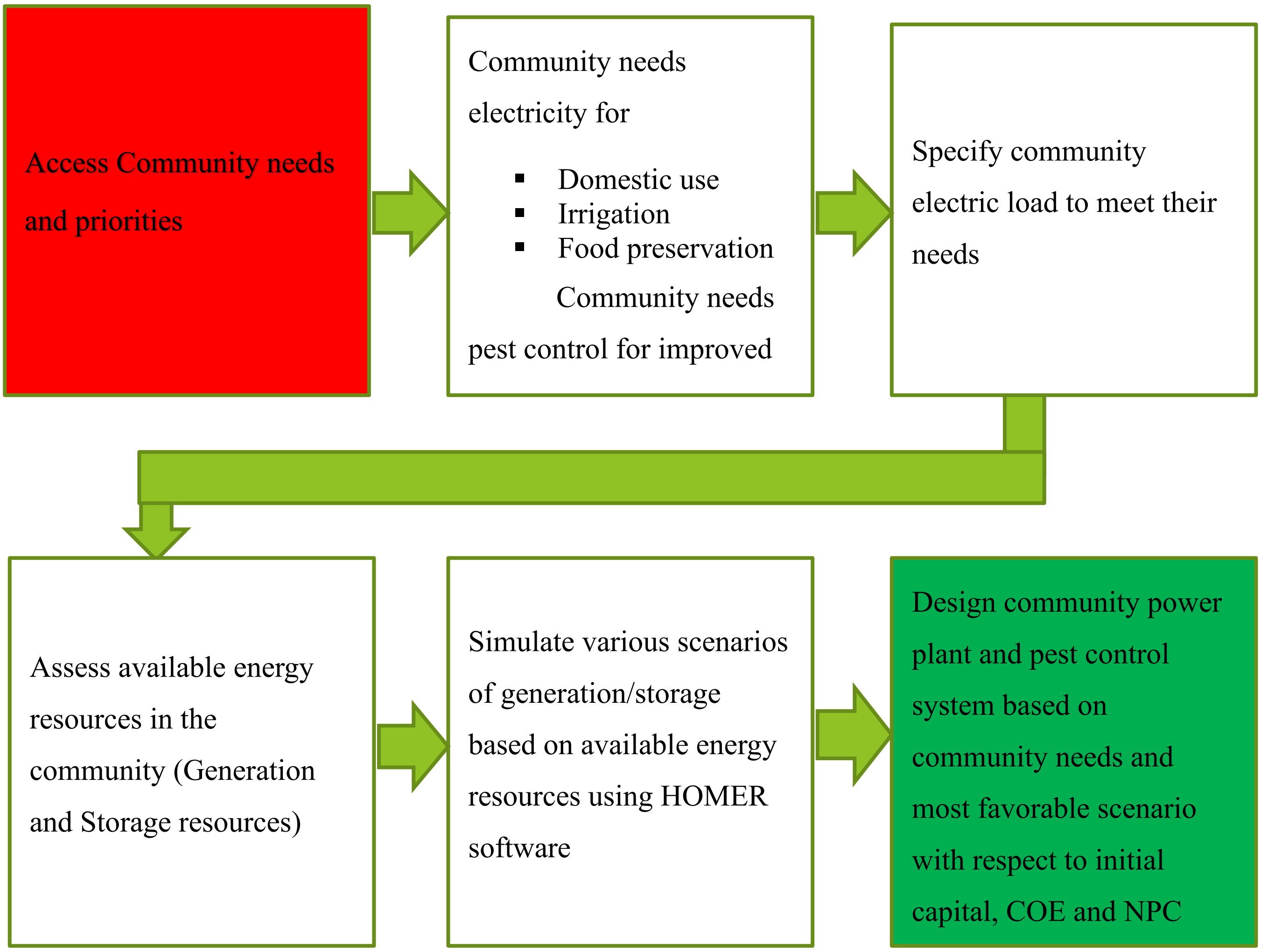

Figure 3.2: Procedure flowchart

3.2 Community Electric Load Profile

The community electrical load in this design comprises the domestic load, irrigation load, pest control load and refrigeration load.

3.2.1 Domestic Electrical Loads

The domestic loads of the community are those of typical tropical rural households. The load is specified in Table 3.1.

Table 3.1: Typical Load Profile of a Rural Household adapted from [125]

Load	Quantity	Power	Total	Use/day	Energy
Bulb	5	10 W	50 W	12 h	0.60 kWh
Charger	3	5 W	15 W	6 h	0.09 kWh
Fan	1	60 W	60 W	10 h	0.60 kWh
Fridge	1	80 W	80 W	24 h	1.92 kWh
TV set	1	80 W	80 W	8 h	0.64 kWh
Laptop	1	60 W	60 W	6 h	0.36 kWh
Others	-	-	-	-	0.25 kWh
Total average daily energy consumption					4.46 kWh

In this study a sample of 50 houses were designated for the community, hence the total average daily energy consumption of the domestic community load is 223 kWh.

3.2.2 Irrigation Water Needs

This community is an agrarian community. For design purposes, it is assumed that each household in the community has an average of an acre of corn farm that needs water for irrigation.

Assuming a furrow irrigation system with efficiency E_a at 80% and a net system capacity C_n required is 0.21 [in/day]. The average peak water use rate W_u in imperial gallon per minute/acre [gpm/acre] can be calculated using equation (1) [126].

$$W_u = 18.86\frac{C_n}{E_a} \tag{1}$$

With $W_u = 5.0\ [\frac{gpm}{acre}]$, considering that 1 imperial gallon is 4.54609 liters, in liters per minute $W_u = 22.8\ [\frac{lpm}{acre}]$. If the duration of irrigation per day is 60 minutes, then the quantity of water required by the community with 50 acres of corn farm would be 68,400 liters equivalent to 68.4 $[m^3]$ of volume. Adding a tolerance of 50%, the community would require approximately 100 $[m^3]$ of water for irrigation. In designing the pumped hydro storage system, this volume must be considered.

Energy required to pump irrigation water is given by equation (2) [127].

$$E_{sw} = \rho ghC \tag{2}$$

where C is the reservoir capacity in $[m^3]$, E_{sw} is the energy stored by pumped water which must be equal to the energy expended in pumping it assuming 100% efficiency for design purposes. ρ is the water density = 1000 [kg/m^3], g is the acceleration due to gravity 9.8 [m/s^2], h is the height of the upper reservoir from the river which is 60 meters. Hence $E_{sw} = \rho ghC = 1000x9.8x60x100 = 58.8x10^6$ $[J]$ = 16 [kWh], approximately 10 [kWh] considering losses.

3.2.3 Community Refrigeration

In the rural areas, most families cannot afford the cost of procuring personal refrigerators, yet this becomes an important facility as rural dwellers are mainly farmers who depend on the sale of agricultural produce to earn a living. In some cases, these farmers suffer losses from perishable products because they do not have refrigerators to preserve the produce to be sold on a later time. This problem can be solved using community refrigeration system.

This section will specify the energy consumption needs for a community refrigerator of 27 $[m^3]$ volume with an equivalent volume of 27,000 liters. The annual energy consumption of household refrigerator-freezers is modeled by equation (3) [128].

$$E\left(\varepsilon, V_{eq}\right) = a(\varepsilon)V_{eq} + b(\varepsilon) \tag{3}$$

where E is annual energy consumption in [kWh]; V_{eq} is equivalent volume in liters; ε is energy efficiency class; a and b are constants associated with the energy class. In this design, the A++ energy class was adopted. The annual energy consumption of the community refrigeration system is 7,165 [kWh] which translates to a daily consumption of approximately 20 [kWh]. This value must be factored into the plant design.

3.2.4 Design of Pest Control System

Rural communities in developing countries mainly depend on agricultural activities as their major sources of income. Animal pests constitute a serious source of losses to farmers. Most of the existing pest management schemes pose environmental and health challenges. Onu and Okpo [12] designed and constructed a solar powered automatic pest control system. This system uses the three signals of sound, motion and light to simulate human presence in the farm. However, the design in [12] is an open loop system that is time dependent without intelligence to know when the animal pest is on the farm. This drawback makes it more power-consuming. Another consequence of the open loop design is that pests with time will get used to the signals and will no longer be scared by them. In the present design, sensors will be incorporated to monitor the presence of rodents and bird pests on the farm and trigger the motion, sound and light signals as response to the presence of pests. In this way the power consumption of the system will be minimized and the efficiency increased as the signals will only be activated in response to pests' presence. Figure 3.2 shows the schematic circuit diagram of the proposed intelligent pest control while Figure 3.3 shows the developed intelligent pest control unit. The design is extendable in such a way to allow for increased range of operation. The number of sensors and output can be increased to expand the range of coverage of the system. The summary of design calculation is shown in Table 3.2.

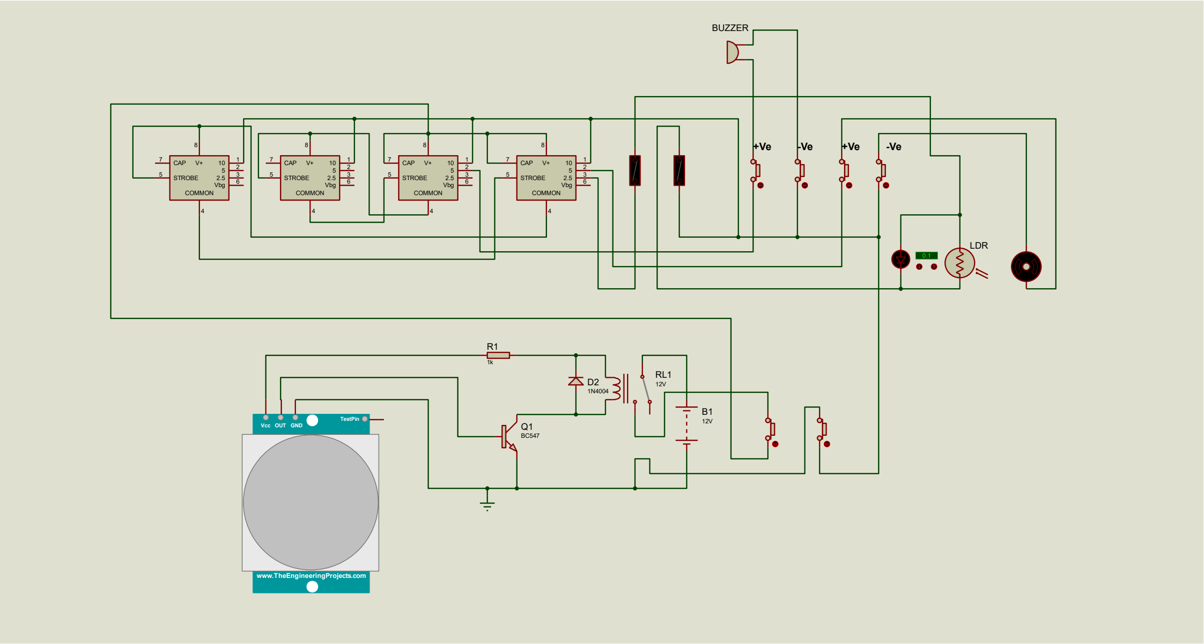

Figure 3.3 Schematic of the intelligent pest control system with single sensor and single output set

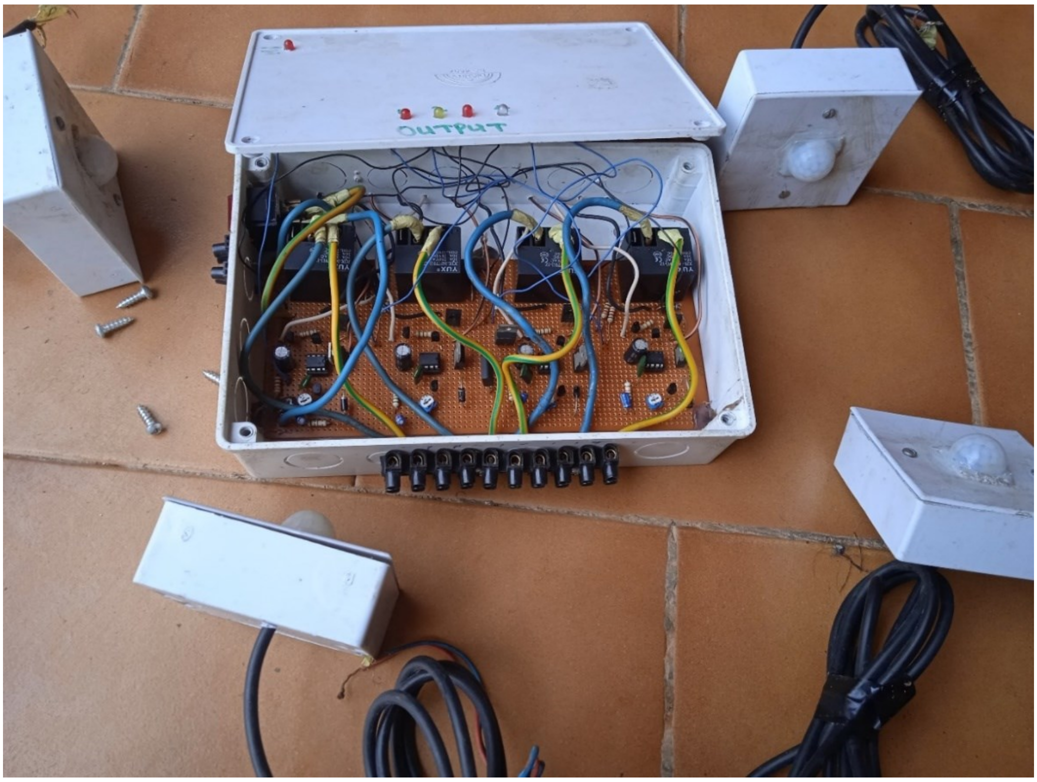

Figure 3.4 Developed Intelligent Pest control unit

Table 3.2: Design Specification for components [12]

S/No	**Component**	**Description**	**Specifications**		
1	Dc Motor	Wiper motor with mechanical accessories for rotary to oscillatory motion conversion	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Rated current	I	2 A
			Speed	N	30 rpm
			Power	$P = IV = 2x12$	24 watts
2	Horn	Trailer truck horn	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Rated current	I	2 A
			Power	$P = IV = 2x12$	24 watts
			Intensity in Decibel	β	100 dB
			Minimal intensity	I_0	10^{-12} w/m^2
			Intensity	$\boldsymbol{\beta = 10log(^{I}/_{I_0})}$ $^{I}/_{I_0} = 10^{\frac{\beta}{10}}$ $I = 10^{\frac{100}{10}} x\ 10^{-12}$	10^{-2} w/m^2
3	Bulbs	Dc bulbs	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Rated current	I	0.5 A
			Power	$P = IV = 0.5x12$	6 watts
4	Resistor	Light Dependent Resistor	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Maximum resistance	R	500 [Ω]
			Maximum Power	$P = \frac{V^2}{R} = \frac{12^2}{500}$	0.288 watts
5	Solar panel	Mono crystalline	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Rated current	I	29 [A]

			Power	P	350 watts
6	Battery	Deep cycle nonspillable	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Rated capacity		300 [AH]
			Charging current	I	25 [A]
			Charging Duration	T	12 Hours
7	Charge controller	PWM	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12/24 volts
			Rated current	I	30 [A]
8	Relays and Timers	Dc Relays and timers	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Rated voltage	V	12 volts
			Rated	I	10 [A]
			Time Range	T	0-60 mins
9	Wire	Stranded cables	**Parameter**	**Formula/Evaluation**	**Value/unit**
			Cross sectional area	A	6 [mm^2]
			Rated Voltage	V	600 volts
10	Circuit Breakers		230 V/30 A		

Table 3.3: Input/output Power Specification for intelligent pest control system [12]

Input		Output(Load)			
Component	Rated Power (watts)	Component	Rated Power (watts)	Quantity	Total Power (watts)
Solar panel	350	Motor	24	2	48
Battery	300	Horn	24	2	48
		bulb	6	10	60
		Total Power			156

To design the community power plant, an assumption of 2 units of pest control system per acre of land with approximately 400 watts per acre will be used. A total of 20 [kW] of power is required to power the 100 units of pest control system to cover 50 acres of farm land. A six-hour operation time per day will be assumed.

3.2.5 Summary of Community Electrical Load

The summary of the electrical load of the community is shown in Table 3.4. The community load profile is shown in Figure 3.4.

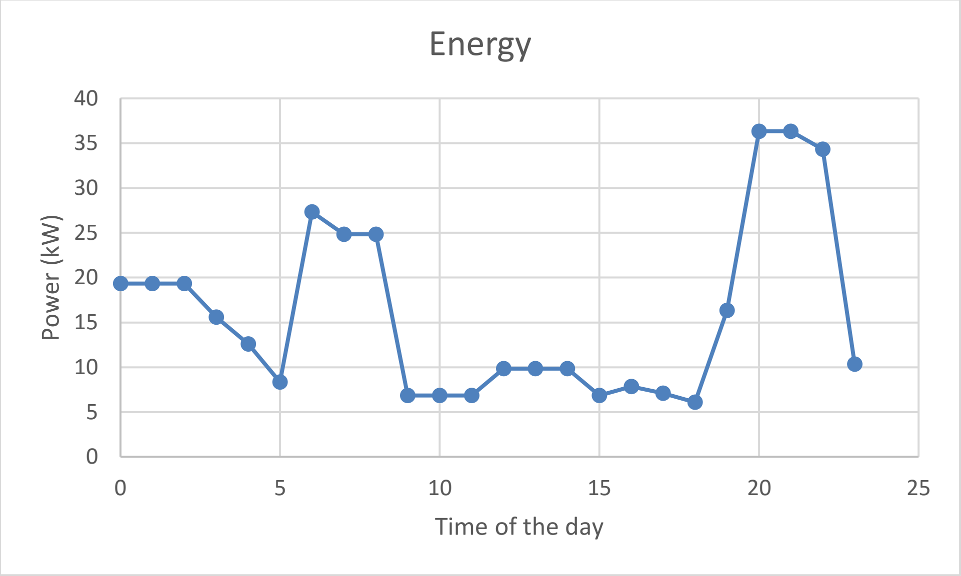

Figure 3.5: Community daily load profile

Table 3.4: Community daily load profile

Hour	Light	Charger	Fan	Fridge	Tv	Laptop	Others	Irrigation	Community Refrigeration	Community	Expansion	Total Power
0	2.5	0.75	3	4	4	3	1.25		0.84			19.34
1	2.5	0.75	3	4	4	3	1.25		0.84			20.34
2	2.5	0.75	3	4	4	3	1.25		0.84			20.34
3	2.5		3	4	4		1.25		0.84			16.59
4	2.5		3	4			1.25		0.84		1	12.59
5	2.5			4					0.84		1	8.34
6	2.5			4					0.84	20		27.34
7				4					0.84	20		24.84
8				4					0.84	20		24.84
9				4				2	0.84			6.84
10				4				2	0.84			6.84
11				4				2	0.84			6.84
12				4		3		2	0.84			9.84
13				4		3		2	0.84			9.84
14				4		3		2	0.84			7.84
15				4				2	0.84			4.84
16				4				2	0.84		1	5.84
17				4			1.25		0.84		1	7.09
18				4			1.25		0.84			7.09
19	2.5	0.75	3	4	4		1.25		0.84			17.34
20	2.5	0.75	3	4	4		1.25		0.84	20		37.34
21	2.5	0.75	3	4	4		1.25		0.84	20		36.34
22	2.5		3	4	4				0.84	20		34.34
23	2.5		3	4					0.84			10.34
Total Energy Consumption per day												**383.16 [kWh]**

3.3 Plant Design and Simulation

The plant will be optimized with HOMER ® (Hybrid Optimization of Multiple Energy Resources) software. Relevant mathematical models will be adopted for the design.

3.3.1 HOMER ® simulation for optimization

To get an optimum design, HOMER ® (Hybrid Optimization of Multiple Energy Resources) software is deployed using the community load profile in Table 4. This community is located on 5°.49.7'N latitude, 7°.55.3'E longitude along Enyum river in southeast Nigeria, which empties into the Atlantic Ocean. The community terrain is shoown in Figures 3.5 and 3.6. Section 1.5 presents a discussion on how the HOMER ® software works. A summary of how HOMER ® computes Net Present Value, Total Annualized Cost, Simple payback, Return on Investment (ROI) and Internal rate of return (IRR) is shown in the appendix section.

Figure 3.8 shows the simulation schematic. HOMER ® reported 7,746 solutions simulated. Out of the total, 3,468 were feasible while 4,278 were infeasible due to capacity shortage constraint, by this the optimization process considered solutions within the limits of the available energy resources. Among the feasible solutions, 2,190 were omitted because 861 lacked a converter, 273 had an unnecessary converter while 1029 had no sources of power generation. Only the best five solutions are shown in Table 5. The generation/storage mix are denoted as follows: Wind turbine =WT; Photovoltaic = PV; Battery storage = BS; Pumped Hydro Storage = PHS.

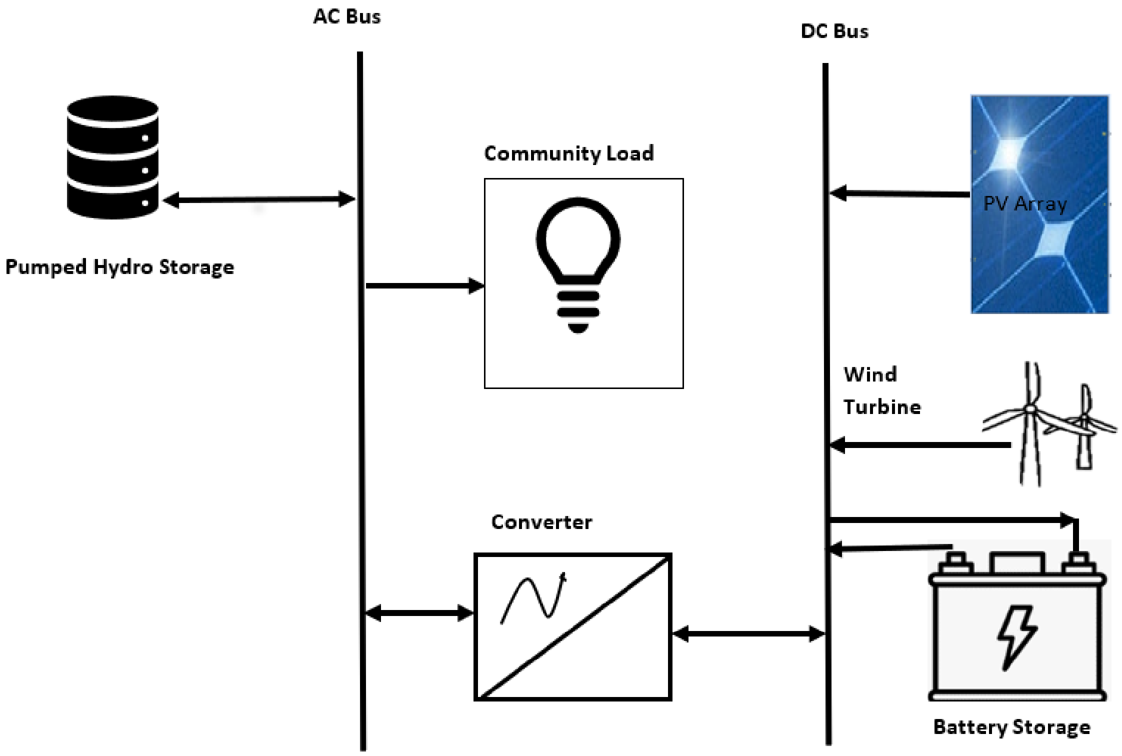

Figure 3.6: Hybrid resource generation schematic

Table 3.5: Different Scenarios of generation/storage for Uhuelem-Amoncha

System ID	**Generation/Storage Mix**	**NPC (US$)**	**COE (US$/kWh)**	**Operating Cost (US$/year)**	**Initial Capital (US$)**
S01 Best**	PV+PHS	823,853	0.456	13,029	655,425
S02	PV+WT+PHS	832,400	0.461	13,338	659,972
S03	PV+WT+BS	1.70M	0.939	37,914	1.21M
S04	PV+BS	1.75M	0.967	37,249	1.27M
S05	WT+PHS	6.17M	3.42	74,659	3.94M

Table 3.5 shows the different scenarios of generation and storage systems for Uhuelem-Amoncha community. The best generation and storage for the plant design is system S01 which is photovoltaic generation with pumped hydro storage system. Based on this information, the choice of a photovoltaic power generation plant with pumped hydro storage is made. In support of this is the fact that the simulated load and storage provided for community irrigation needs, pest control, community refrigeration and domestic consumption.

3.4 Plant design models

The best system architecture from HOMER ® simulation is as follows:

Rating of photovoltaic system is 208 [kW];

5 units of PH245 Pumped Hydro Storage system;

AC/DC converter is rated 87.2 [kW];

3.4.1 Photovoltaic System

According to the Solar Radiation Database of the National Renewable Energy Laboratory (NREL), the average global solar radiation at Uhuelem-Amoncha, Nigeria, is 4.5 [kWh/m²] a day [56]. It is expected that the photovoltaic system will produce more energy than necessary for community use. It is common to have days with low solar radiation due to rain or even the presence of clouds.

The photovoltaic generator aims to meet two different demands in the community. During the day, it is expected that there will be electricity from solar sources to store water in the reservoir and supply energy to the community.

The energy produced by a PV power plant is given by Equation (4) [57]. The scaled daily average energy consumption of the community is 383.16 [kWh]. Applying Equation (4), the nominal plant power of 221 [kWp] would serve the community with 2.5 days of storage. A set of 481 typical photovoltaic 460 [W] solar panels is needed to meet the load requirements.

$$E = P_n \left(\frac{A_p}{P_p}\right) R_m \eta_p \tag{4}$$

where P_n is the nominal power of the plant in [kWp], $A_p = 2.11\ [m^2]$, $P_p = 0.460\ [kW]$, and η_p refer to the area, nominal power, and yield of a typical solar panel (i.e. η_p is the efficiency of the photovoltaic panels at 21%), and $R_{m=}$ 4.5 $[\mathrm{kWh/m^2}]$ a day is the average global solar radiation. Given that $E = 383.16\ [kWh]$, $P_n = 88394.19\ [W]$. Applying the safety factor of 2.5 yields a nominal plant power of 221 [kWp]. The optimization result gave 5 hours of unmet electrical load hence the design value was adjusted to 221 [kWp] instead of the optimization value of 208 [kWp] using a safety factor of 2.5 times on $P_n = 88394.19\ [W]$.

Equation (4) defined the power plant size based on average daily solar irradiation. To supply the total electrical demand during night and cloudy days, the pumping system must pump and store enough water to provide energy to the community during these situations. This is especially important at peak consumption between 20:00 and 21:00. Defining the amount of energy to be stored in the upper reservoir is an optimization problem due to uncertain weather conditions. In this sense, cloudy periods for up to four days are expected even in a location with high solar irradiation. It is also important to remember that even on cloudy days, the solar system can generate energy with a reduced capacity.

For this reason, the photovoltaic system was designed with a safety factor of 2.5 times larger than that theoretical value. This will maximize the value of day-time energy cloudy days [131]. With this information, it is possible to size the project's photovoltaic system to meet the community's energy demand and water consumption. As a result, the photovoltaic system will be approximately 221 [kWp] of installed power. As shown in the *HOMER*® software system architecture the PV system compares closely. The inverter size is the same as specified by *HOMER*®. The simulation with the software included historical meteorological data, thus giving greater reliability to the installed power sizing.

3.4.2 PAT and Hydro storage System

Pump mode model of the PAT

The models adopted in this design were according to [58]. When solar radiation is available, the pump as turbine (PAT) operates as a pump storing water in the upper reservoir. The electrical energy used by the pump to store water in the upper reservoir is modelled by Equation (5).

$$E_p = \frac{\rho g h Q_p}{\eta_p} \tag{5}$$

where E_p is the the electrical power delivered to the pump by the PV system, ρ is the water density = 1000 [kg/m^3], g is the acceleration due to gravity 9.8 [m/s^2], h is the height of the upper reservoir from the river, Q_p is the volumetric flow rate in [m^3/s] of water from the pump to the upper reservoir, while η_p is the pump efficiency. The effective head height of the site according Figure 3.5 is 60 $[m]$ as obtained from Google Earth. The capacity of the storage will be increased by 40% to make for the shortage in effective head. Hence the PAT system rating will increase by 40%. The system would require additional 2 units of PH245 pumped hydro storage systems to compensate the head height difference of 40 m since the equation relating the head height h capacity of the reservoir C and energy stored by the reservoir is given E_{sw} by $E_{sw} = \rho g h C$ A total of 7 units PH245 pumped hydro storage systems is required for adequate storage.

Generator mode model of the PAT

During the absence of generation from the PV system, the PAT operates as a turbine generating electric power from the potential energy stored by the water in the upper reservoir. The electrical energy generated by the turbine is given by Equation (6).

$$E_G = \rho g h Q_t \eta_G \tag{6}$$

where E_G is the electrical energy generated by the PAT running as a turbine, ρ is the water density = 1000 [kg/m^3], g is the acceleration due to gravity 9.8 [m/s^2], h is the height of the upper reservoir from the river, Q_t is the volumetric flow rate of water in [m^3/s] from the upper reservoir to the turbine, while η_G is the generator efficiency. The PH245 pumped hydro storage system can function in reversible mode as a generator with the same efficiency. The same machine used in storage as a pump will be in generation as a turbine.

Reservoir Specifications

The quantity of water in the upper reservoir at any instant of time is specified by Equation (7).

$$Q_{sw} = (1-\sigma)Q_{sw}(t-1) + \int_{t=1}^{t} Q_p\,(t)dt - \int_{t=1}^{t} Q_t\,(t)dt \tag{7}$$

where Q_{sw} is the quantity of stored water in [m^3], σ is the percentual relative quantity of water lost to evaporation and leakages. The combined capacity of the 7 units of PH245 pumped hydro storage system is 7 million liters of water.

The state of charge of the upper reservoir and total energy stored in the reservoir are given by Equation (8) and (9), respectively.

$$SOC(t) = \frac{Q_{sw}(t)}{Q_{swmax}(t)} \tag{8}$$

constrained by $Q_{swmin} \leq Q_{sw} \leq Q_{swmax} = C$. Considering that:

$$E_{sw} = \rho g h C \tag{9}$$

where C is the reservoir capacity, E_{sw} is the energy stored in the upper reservoir, SOC is the state of charge of the upper reservoir. The capacity of the complete storage is $7{,}000\ [m^3]$

As stated by de Doile et al [57], the NPC is given by (10), where C_0 is the initial cost, CF_i is the annual cash flow, and r is the project expected return rate in a period of n years.

$$NPC = -C_0 + \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} \tag{10}$$

3.5 Plant Specification

The specifications of the design plant for Uhuelem-Amoncha community are shown in Table 3.6.

Table 3.6: Summary of plant specification

Parameter	**Specification**
Nominal Power	221 [kW]
PV system	481 units of 460 [W] solar panels
PAT system	7 units of 20.5 [kW]
Total Reservoir capacity	7000 [m^3]
AC/DC converter	87.2 [kW]

3.6 Plant Expansion Chart

The community may in the future want to expand the capacity of the plant. Table 3.7 gives the plant expansion specification for the designed system. Energy production of 480 [kWh] would require 233

[kWp] of solar panel rating, (8+3) units of PH245 pumped hydro storage system and 79.1 [kW] inverter. Energy production of 550 [kWh] per day would require 286 [kWp] of solar panel rating, (8+3) units of PH245 pumped hydro storage system and 93.4[kW] inverter. Energy production of 1000 [kWh] per day would require 508 [kWp] of solar panel rating, (15+6) units of PH245 pumped hydro storage system and 214 [kW] inverter. Energy production of 1500 [kWh] per day would require 735 [kWp] of solar panel rating, (24+10) units of PH245 pumped hydro storage system and 313 [kW] inverter. Energy production of 2000 [kWh] per day would require 1052 [kWp] of solar panel rating, (28+11) units of PH245 pumped hydro storage system and 352 [kW] inverter.

Table 3.7: Plant Capacity Expansion Chart

Energy Production (kWh)	**PV Rating (kWp)**	**PH245 Pumped Hydro Storage System**	**Inverter Rating (kW)**
480	233	8 units + 40%	79.1
550	286	8 units + 40%	93.4
1000	508	15 units +40%	214
1500	735	24 units + 40%	313
2000	1052	28 units + 40%	352

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Results and Discussion

The results of the plant design are presented in two parts namely generation/consumption and economics/costs. This is because the viability of the plant design depends on its capacity to generate the required energy within a reasonable cost.

4.1.1 Energy Generation and Consumption

Figures 4.1 and 4.2 show the total electrical load served, photovoltaic power output, pumped hydro storage input power and unmet electrical load. The Figures reveal that the system met all the electrical load connected it throughout the year except for 5 hours on August 4. This resulted a power supply probability of 99.9%. The designed plant can meet the energy needs of the community around the year with 99.9% probability.

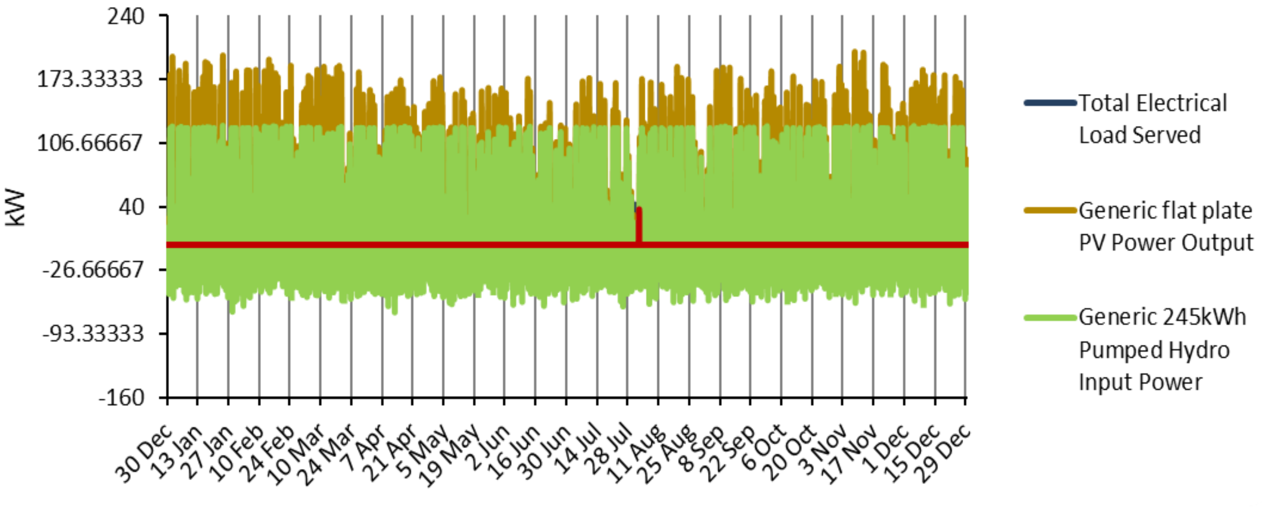

Figure 4.1: PV Power; Storage and Load

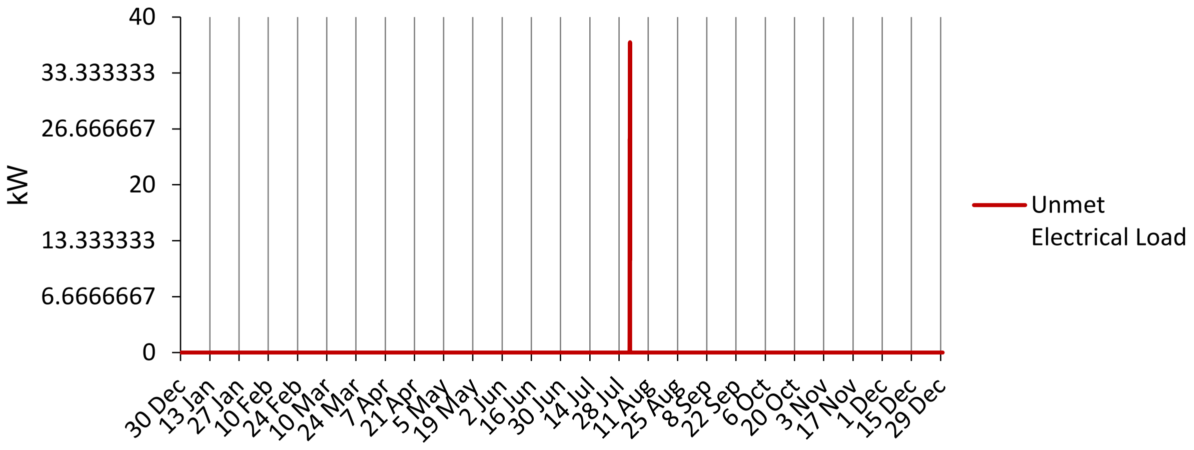

Figure 4.2: Unmet Electrical Load

The unmet electrical load represents the time duration for which the system is not able to supply the design load due to resource shortage. Unmet load is electrical load that the power system is unable to serve. It occurs when the electrical demand exceeds the supply. In this design the unmet electrical load is 5 hours out of the total of 8760 hours in the year.

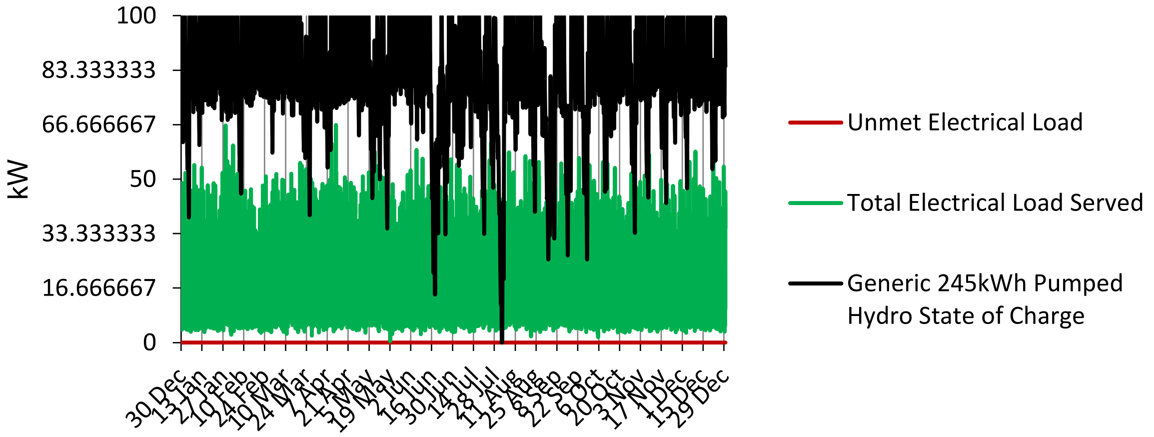

Figure 4.3: Unmet Electrical load; Total Electrical load and pumped hydro state of charge

Figures 4.4 and 4.5 show the inverter power output and the total electrical load served, respectively. The two Figures are direct mirror of each other, implying that the inverter output matches the electrical load.

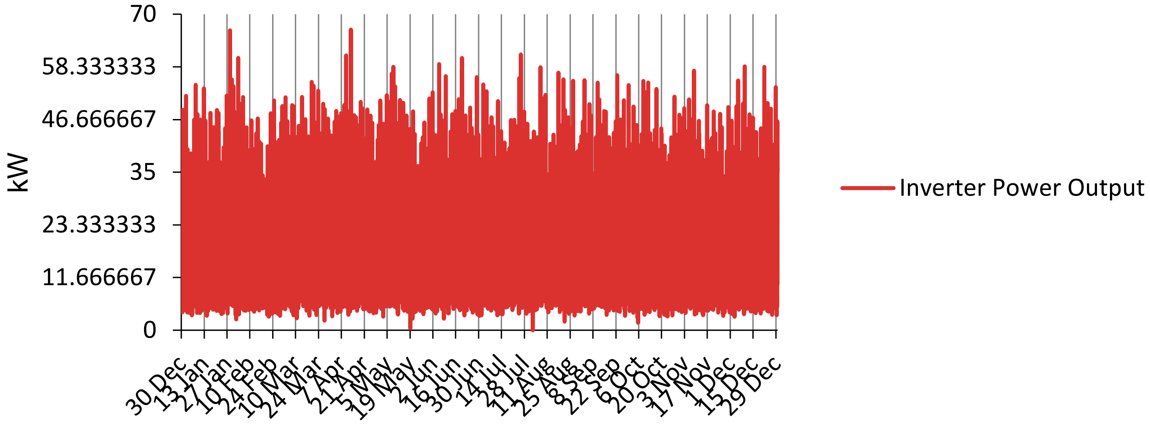

Figure 4.4: Inverter output power

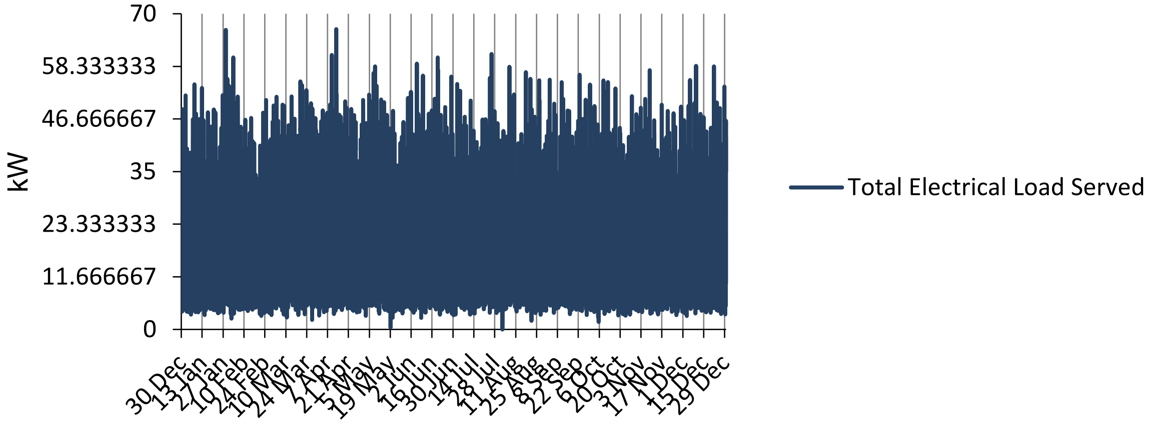

Figure 4.5: Total Electrical Load Served

4.1.2 System Costs and Economics

Cost is a very important aspect of any design. The acceptability and economic sustainability of any engineering design depend on the system's operation and maintenance cost. The energy provided by a plant can only be useful for economic application if the cost of energy is within the affordable limit of the consumers. Table 4.1 shows the cost summary of the designed plant. An important consideration for the economic sustainability of the system after installation is the cost of energy COE. This must be compared with other alternative energy sources to ascertain preference. The cost of energy COE of this design is 0.456 [US$/kWh]. This is different from the cost of energy COE obtained in Onu et al. [132] due to difference in the head heights of the upper reservoirs arising from changes in the location of the upper reservoir along the river. In the community considered in this design, people rely heavily on using petrol generators for electric power supply as the grid supply is barely available. The local cost of one liter of petrol is two hundred Nigerian naira (₦200.00). A family running a 3.0 [kVA] petrol generator needs at least 20 liters to run the generator for 24 hours to power their domestic electrical load. This amounts to four thousand and eight hundred Nigerian naira (₦ 4800.00) daily. At the current exchange rate of the US$ against the Nigerian naira ₦ of US$1 to ₦420.46, the energy cost of the designed plant in this study will amount to 191.73 [₦ /kWh]. Each family's energy consumption in this design is 4.46 [kWh] per day. This implies that the family will spend a total of eight hundred and fifty-five-naira twelve kobo (₦ 855.12) to power their domestic electrical load for the same 24 hours they would have spent four thousand and eight hundred Nigerian naira (₦ 4800.00) using a petrol-powered generator. The result is 82% reduction in the present energy cost in the community. Hence, the design offers a cheaper alternative energy cost.

Table 4.1 System cost summary

Cost Component	**Amount**
Net Present Cost NPC	US$ 823,853
Cost of Energy COE	0.456 [US$/kWh]
Annual Operating Cost	US$ 13,338
Initial Capital	US$ 655,425
Capital Cost	US$ 519,277

4.1.3 System Sensitivity Analysis

For more in-depth analysis/conclusions, a sensitivity analysis was conducted concerning the community's electricity consumption, as illustrated in Figures 4.6, 4.7 and 4.8. This is particularly important since although reliable data is used to estimate the consumption, it might be slightly different at certain times from expected.

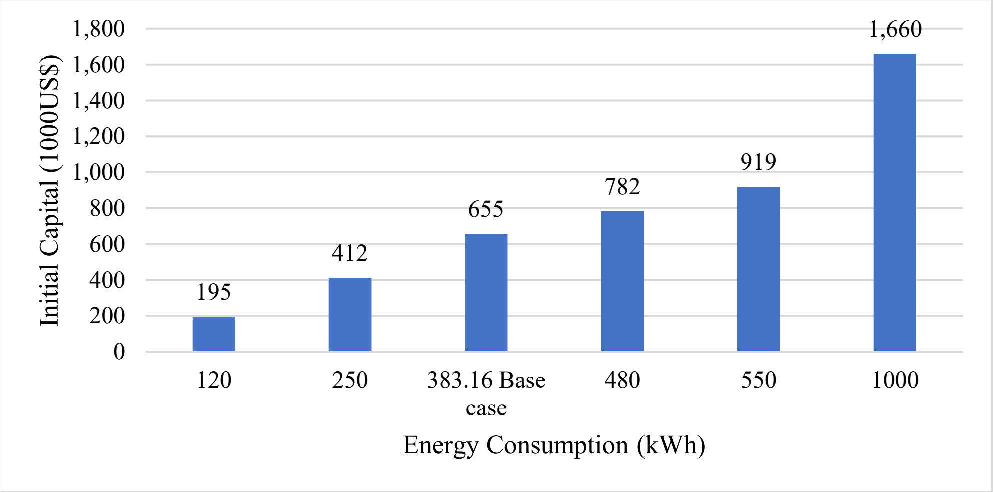

Figure 4.6 Initial capital

The capital increases with increase in the generation capacity of the plant.

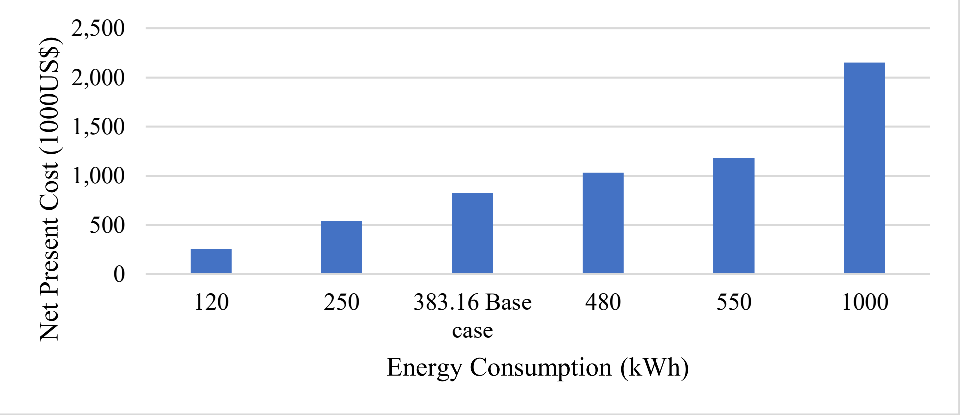

Figure 4.7 Net present cost

The net present cost increases with increase in generation capacity of the plant.

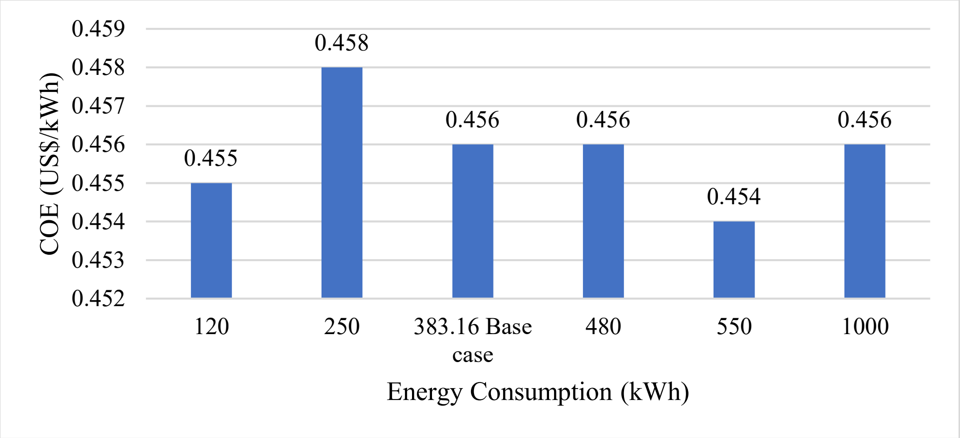

Figure 4.8 Cost of energy

The COE results are relatively robust in terms of electricity consumption. Therefore, the system would perform satisfactorily even when the consumption is varied. The implication is that the cost of energy will remain relatively the even when the quantity of consumed electricity changes as a result of capacity expansion.

CHAPTER 5 CONCLUSION

5.1 Conclusion

Seasonal and location dependence of renewable energy resources have limited their applications in power generation. Energy storage systems are promising solutions to the intermittence of renewable energy resources. Rural electricity grids are faced with economic sustainability challenges due to low power demand and poverty. A rural grid design around economic drivers like agriculture and micro industries can mitigate poverty and improve the economic sustainability of rural grids. Microgrids are flexible power system technologies that can be adopted in developing economies for rapid energy access.

This work proposed a sustainable integrated strategy to help an African community to access electrical energy, water supply for irrigation and domestic use, community pest control system and community refrigeration scheme. HOMER ® (Hybrid Optimization of Multiple Energy Resources) software was deployed to optimize the design.

A photovoltaic power generation plant was designed with a nominal capacity of 221 [kW]. The power supply probability of the plant is 99.9%. The cost of energy (COE) offered by design is 0.456 [US$/kWh] which is 82% lower than the current cost of energy in the project community based on generation through petrol generators. The System has 100% renewable energy penetration.

The plant is designed to power 50 households with a daily domestic energy consumption of 4.46 [kWh] each. The plant capacity also covers the irrigation water requirement of 50 acres of corn farms. A total of 100 units of designed intelligent pest control system will be powered by the plant. A community refrigeration scheme of 27 [m^3] equivalent volume is also part of the plant design load.

This study has attempted to proffer solution to the problems of lack of energy access in a rural Nigerian community. The challenge of economic sustainability of rural electric grids was addressed through the integration of agricultural facilities as economic drivers.

The study of microgrids in developed and developing economies shows that the two economies have different needs for microgrids. As for the developed economies, the interest is in energy security, resilience, energy democracy, digitalization, and decarbonization. On the other hand, the developing economies are grappling with the challenge of energy access. Fortunately, microgrid technologies can take care of the identified interests in developed and developing economies. For a world of equity and inclusion, microgrids are viable energy system designs that can be adapted to serve the various needs of all levels of the economy. They are not limited by topography, hydrology, and distance, as in the case of conventional grids. They are flexible enough to serve any desired interest. Therefore, microgrids may work as technological and social drivers of changes in countries of different economic profiles. Political power and willingness to create the laws and business incentives are the key points to mainly provide the human rights and sustainably reduce energy poverty since financial analysis will easily prove the viability of microgrids, both in developed or developing countries.

As a possible solution to energy shortages in rural communities, utility companies can partner with the government, international donor agencies, research organizations like Forum for Agricultural Research in Africa (FARA), and the community to finance, execute and manage viable microgrid projects for an improved standard of living in the affected communities. It is important to note that HOMER® does not calculate/estimate social benefits. Hence the integral social and environmental benefits derivable from the irrigation, water supply, pest control and community refrigeration components of the design is a subject of future socioeconomic research.

5.2 Contribution

This study contributes a rural electrical grid design for social inclusion and economic sustainability through Agriculture as an economic driver.

A pumped hydro storage (PHS) site with sufficient natural storage height and water source was discovered in Uhuelem-Amoncha community that can be expanded to accommodate the electrical energy need of Afikpo metropolis and its environs.

5.3 Future Work

HOMER ® (Hybrid Optimization of Multiple Energy Resources) at this time was not capable of evaluating all the socioeconomic and environmental benefits from the irrigation, pest control, energy access and community refrigeration schemes.

There is need for future research to develop a solution to evaluate the overall benefits of these systems.

5.4 Publication from this research

U. G. Onu, G. S. Silva, A. C. Zambroni de Souza, B. D. Bonatto, and V. B. Ferreira da Costa, "Integrated design of photovoltaic power generation plant with pumped hydro storage system and irrigation facility at the Uhuelem-Amoncha African community," *Renewable Energy*, Oct. 2022, https://doi.org/10.1016/j.renene.2022.08.059 .

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APPENDIX: SIMULATION REPORT

Microgrid Proposal

PREPARED FOR:
Uhuelem-Amoncha Community
RWHC+2F, 490101, Amoncha, Nigeria

PREPARED BY:
Uchenna Godswill Onu

This proposal was generated using HOMER Pro, a dynamic software engine that runs complex simulations of your hybrid electrical system's energy data and system components to determine the least-cost solution and most effective risk-mitigation strategies. Originally developed at the US Department of Energy's National Renewable Energy Laboratory (NREL), HOMER software set the global standard for optimizing microgrid design. More than 200,000 HOMER Pro users worldwide have produced economic feasibility studies, system design, engineering insight, and energy cost savings.

Table of Contents

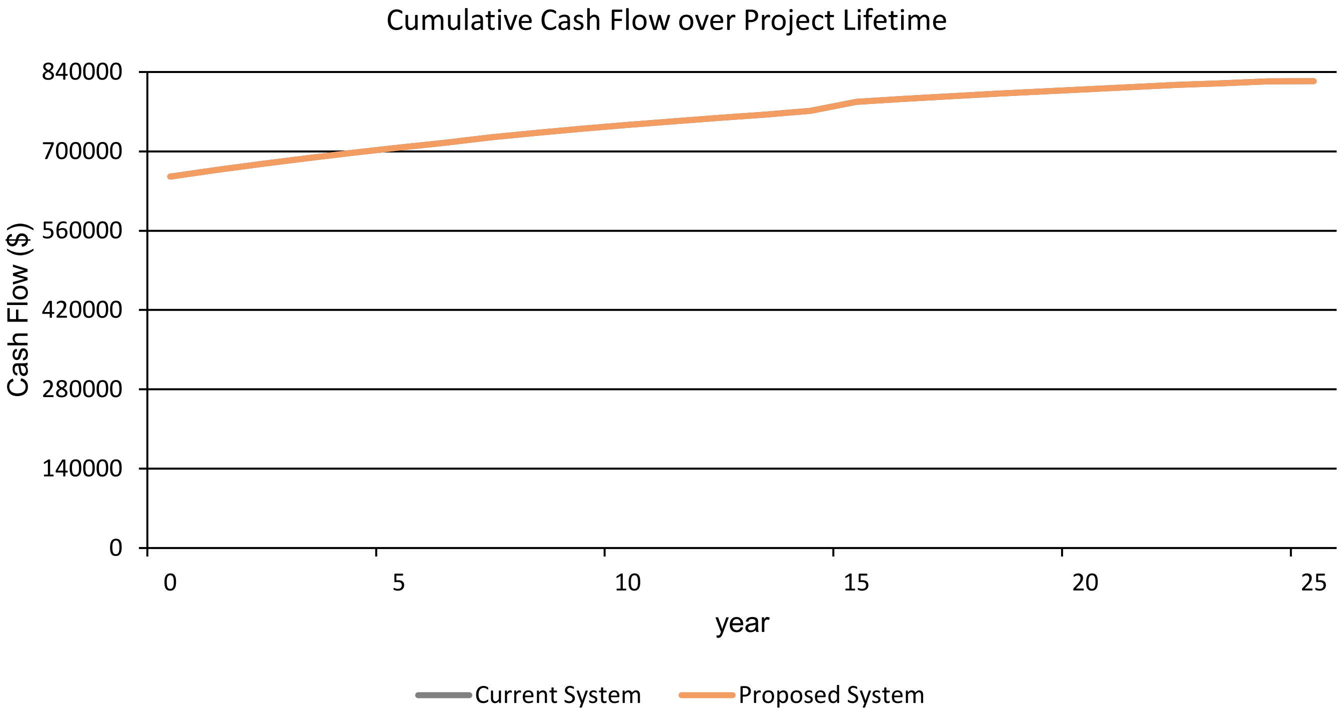
PREPARED BY:
Your Name,
Your Title, Your Company Name,
Your Email,
Your Phone Number

Project Summary

CURRENT SYSTEM

The electric needs of RWHC+2F, 490101, Amoncha, Nigeria are met with 208 [kW] of PV and 1,271 [kWh] of battery capacity. Its operating costs for energy are currently 13,029 [US$] per year.

We recommend not making alterations to the current system because it is the most economical choice.



PREPARED BY:
Your Name,
Your Title, Your Company Name,
Your Email,
Your Phone Number

Your Company Name

ABOUT YOUR COMPANY NAME

Use this section to introduce your company name and explain what your business does, where you operate (or the markets you serve), and how long you’ve been doing it for. About Us page is the ideal place to accommodate several objectives:

- Communicate the story of your business and why you started it.
- Describe the customers or the cause that your business serves.
- Explain your business model or how your products are made

Customer Testimonials

Use this space to provide statements made about your company by satisfied customers. Quotes and positive comments are valuable to prospective clients as they evaluate their options and decide whether your company’s services provide the best solution to fit their needs. Testimonial statements demonstrate how others have benefited from your company’s services, making them a powerful tool for establishing trust and encouraging potential clients to take action.

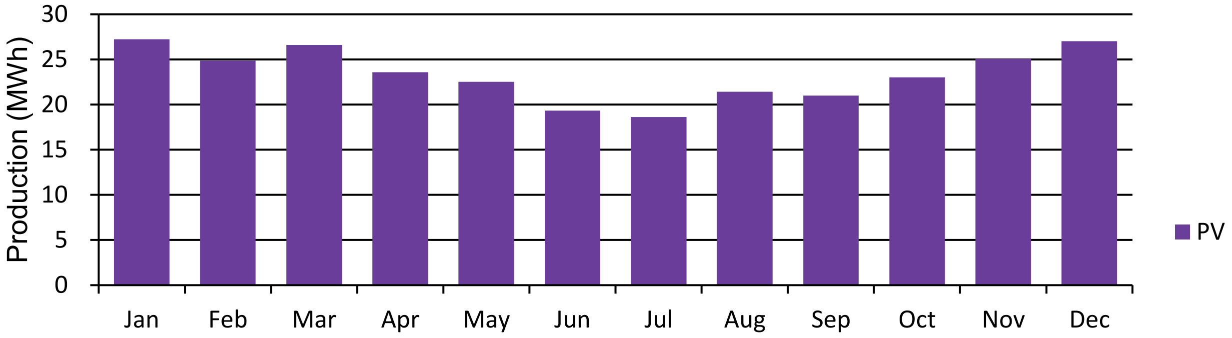
—John J. Client, CEO - Your Happy Client, Inc.

PREPARED BY:
Your Name,
Your Title, Your Company Name,
Your Email,
Your Phone Number

Consumption Summary

Electric Consumption

This microgrid requires 383 [kWh/day] and has a peak of 67 [kW]. In the proposed system, the following generation sources serve the electrical load.



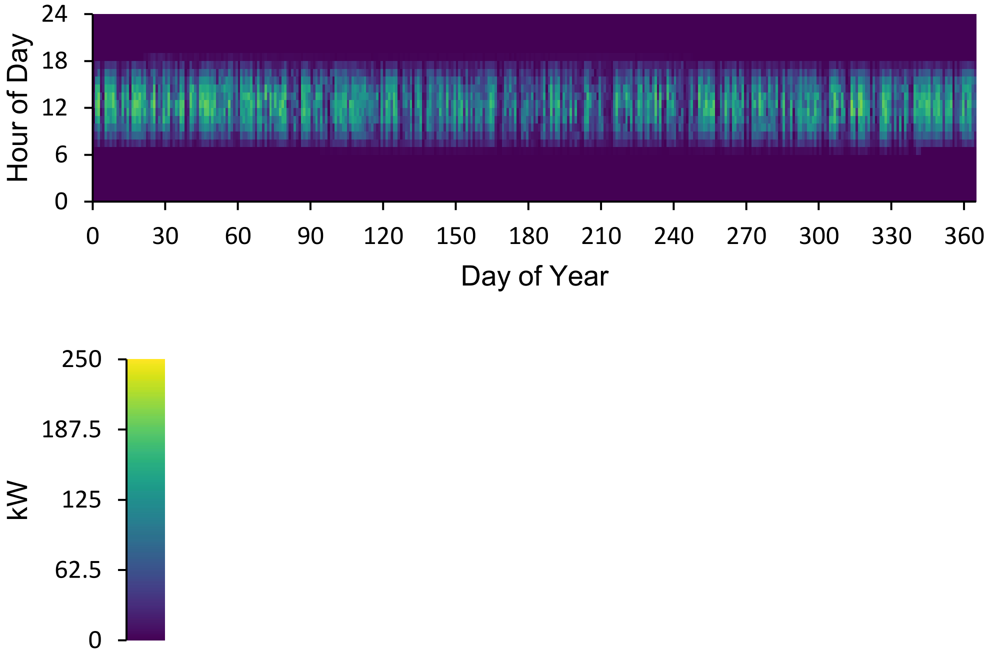
Engineering Details

PV: Generic flat plate PV

The Generic PV system has a nominal capacity of 208 [kW]. The annual production is 280,282 [kWh/yr].

Rated Capacity	208 [kW]
Capital Cost	519,277 [US$]
Specific Yield	1,349 [kWh/kW]
PV Penetration	200 %

Total Production	280,282 [kW]
Maintenance Cost	2,077 [US$/yr]
LCOE	0.151 [US$/kWh]



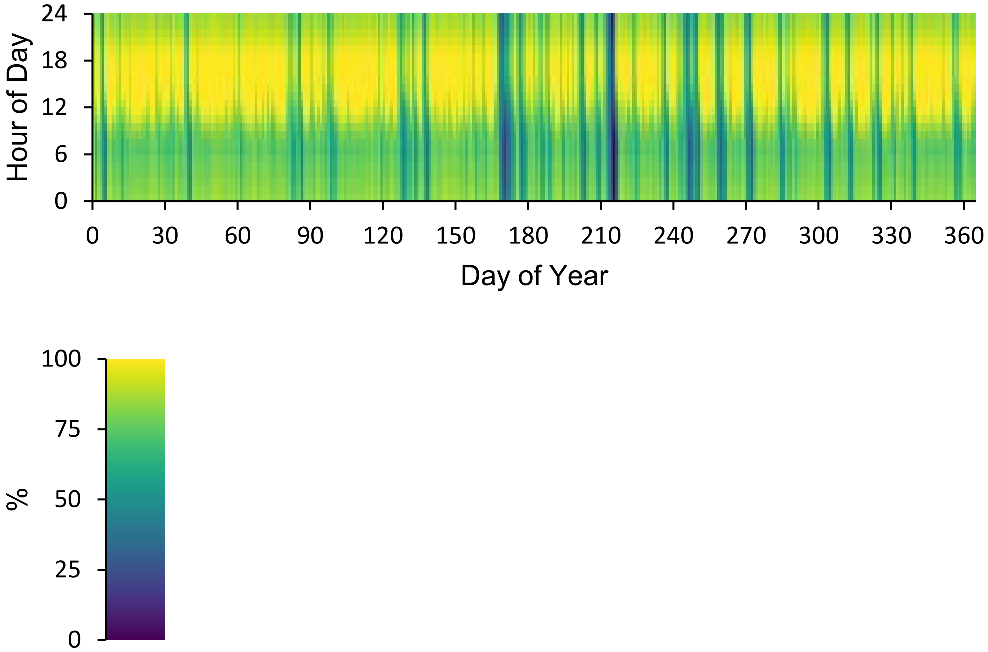
Storage: Generic 245 [kWh] Pumped Hydro

The Generic storage system's nominal capacity is 1,271 [kWh]. The annual throughput is 119,409 [kWh/yr].

Rated Capacity	1,271 [kWh]
Annual Throughput	119,409 [kWh/yr]
Maintenance Cost	10,000 [US$/yr]
Autonomy	79.6 hr

Expected Life	7.00 yr
Capital Costs	110,000 [US$]
Losses	25,187 [kWh/yr]

Engineering Details

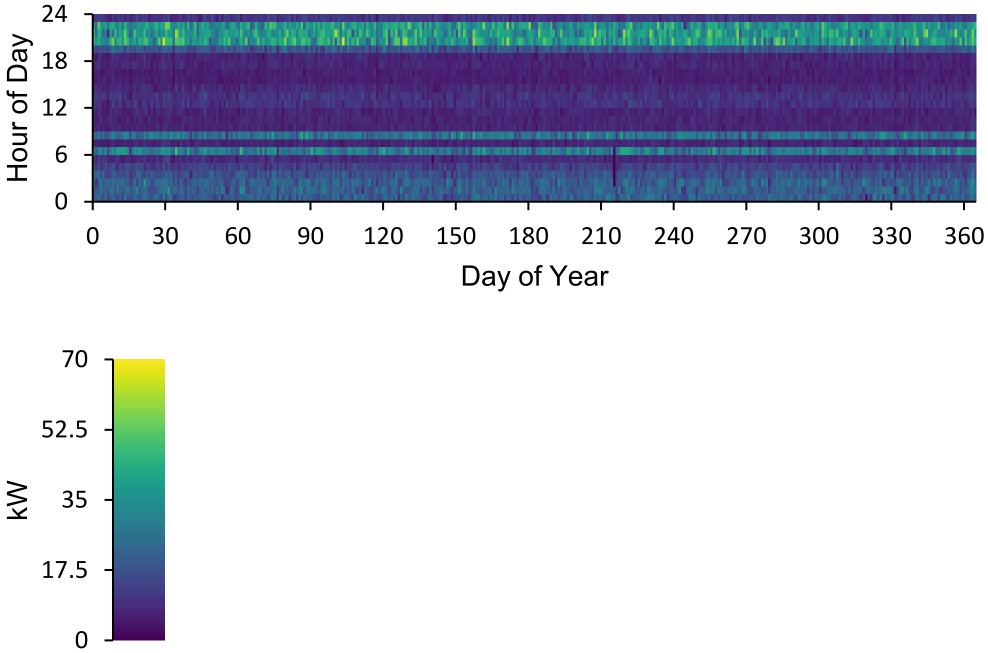


Engineering Details

Converter: System Converter

Capacity	87.2 [kW]
Mean Output	16.0 [kW]
Minimum Output	0 [kW]
Maximum Output	66.6 [kW]
Capacity Factor	18.3 %

Hours of Operation	8,756 [hrs/yr]
Energy Out	139,741 [kWh/yr]
Energy In	147,095 [kWh/yr]
Losses	7,355 [kWh/yr]



Cash Flows

Project Lifetime 25 years

Expected Inflation Rate 2.0%

Nominal Discount Rate 8.0%

Real Interest Rate 5.9%

Year	1	2	3	4	5	6	7	8	9	10
Generic 245kWh Pumped Hydro	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
Generic flat plate PV	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)
System Converter	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Year	11	12	13	14	15	16	17	18	19	20
Generic 245kWh Pumped Hydro	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
Generic flat plate PV	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)
System Converter	$0.00	$0.00	$0.00	$0.00	($26,148)	$0.00	$0.00	$0.00	$0.00	$0.00

Year	21	22	23	24	25
Generic 245kWh Pumped Hydro	($10,000)	($10,000)	($10,000)	($10,000)	($10,000)
Generic flat plate PV	($2,077)	($2,077)	($2,077)	($2,077)	($2,077)
System Converter	$0.00	$0.00	$0.00	$0.00	$8,716

Glossary and Abbreviations

Net Present Value

The total net present cost (NPC) of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. HOMER calculates the total NPC by summing the total discounted cash flows in each year of the project lifetime.

Total Annualized Cost

Is the annualized value of the total net present cost. The annualized cost of a component is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that component. HOMER calculates annualized cost by first calculating the net present cost, then multiplying it by the capital recovery factor.

Simple payback

Is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system.

Return on Investment (ROI)

Is the yearly cost savings relative to the initial investment. The ROI is the average yearly difference in nominal cash flows over the project lifetime, divided by the difference in capital cost.

Internal rate of return (IRR)

Is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero.

Refer to HOMER Pro Online Help Manual

Abbreviations

PH 245	Generic 245 [kWh] Pumped Hydro
LA ASM	Generic 1 [kWh] Lead Acid [ASM]
G3	Generic 3 [kW]
PV	Generic flat plate PV
Converter	System Converter

About HOMER Pro

HOMER® Pro simulates engineering and economic feasibility of microgrid or distributed energy systems that are off-grid or tied to an unreliable grid and enables the design of least-cost electrical systems and risk-mitigation strategies. The software provides insight into cost-effectively combining conventional and renewable energy, storage, grid resources (where available), and load management.

In a single data run, HOMER Pro simulates the operation of a hybrid microgrid or distributed energy system for an entire year, evaluating and optimizing the electrical system design, load profiles, components, fuel costs, and environmental variables. The simulation produces key information on technical performance, risk-mitigation, and projected cost-savings to inform system design and optimization. Results are presented in a succinct Microgrid Proposal. For more information, visit HomerEnergy.com.

About HOMER Energy by UL

HOMER software is used by more than 200,000 users in 193 different countries.

HOMER Energy by UL is the developer and distributor of HOMER software, a global standard for energy modeling tools that analyze solar-plus-storage, microgrids, and other distributed energy projects.

HOMER software helps engineers and project developers navigate the complexities of designing cost-effective and reliable microgrids that combine traditional and renewable generation sources. The company makes two software platforms: HOMER Pro for the design of least-cost hybrid microgrid or distributed energy systems for use off-grid or when tied to an unreliable grid; and HOMER Grid, which helps design behind-the-meter solar-plus-storage systems to reduce costs and lower carbon footprints.

Since its founding in Boulder, Colorado in 2009, HOMER Energy software has proven effective for analysing complex distributed energy systems, including grid-tied hybrid renewable microgrids and situations where the grid is insufficiently reliable, such as islands and remote communities. In 2019, HOMER Energy was acquired by UL. More than 200,000 HOMER Pro users in over 190 countries have produced economic feasibility studies, system design, engineering insight, and energy cost savings. Learn more at www.homerenergy.com.

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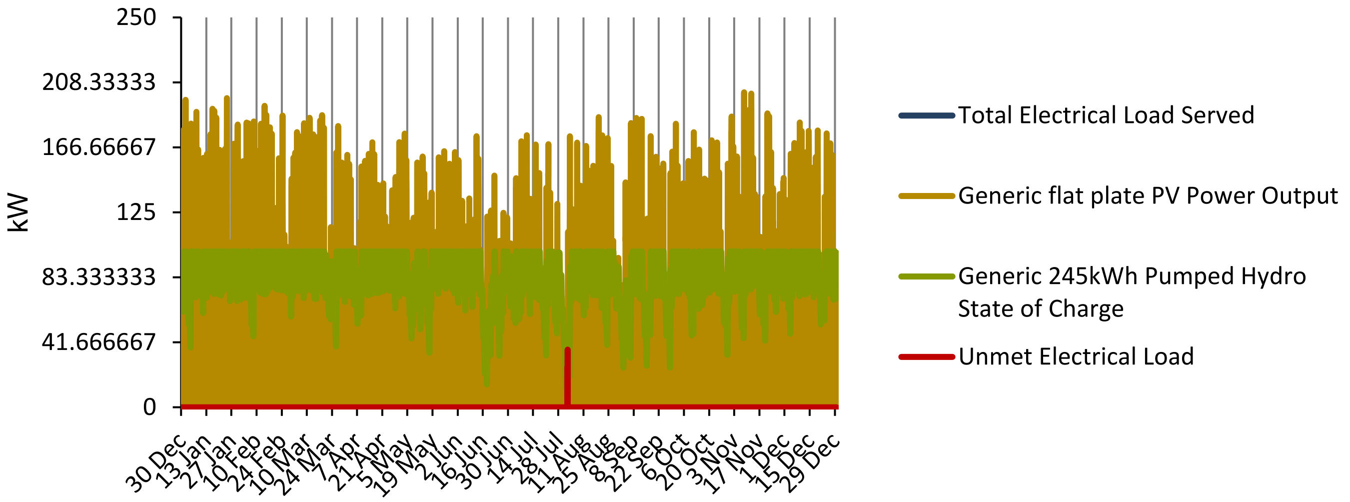
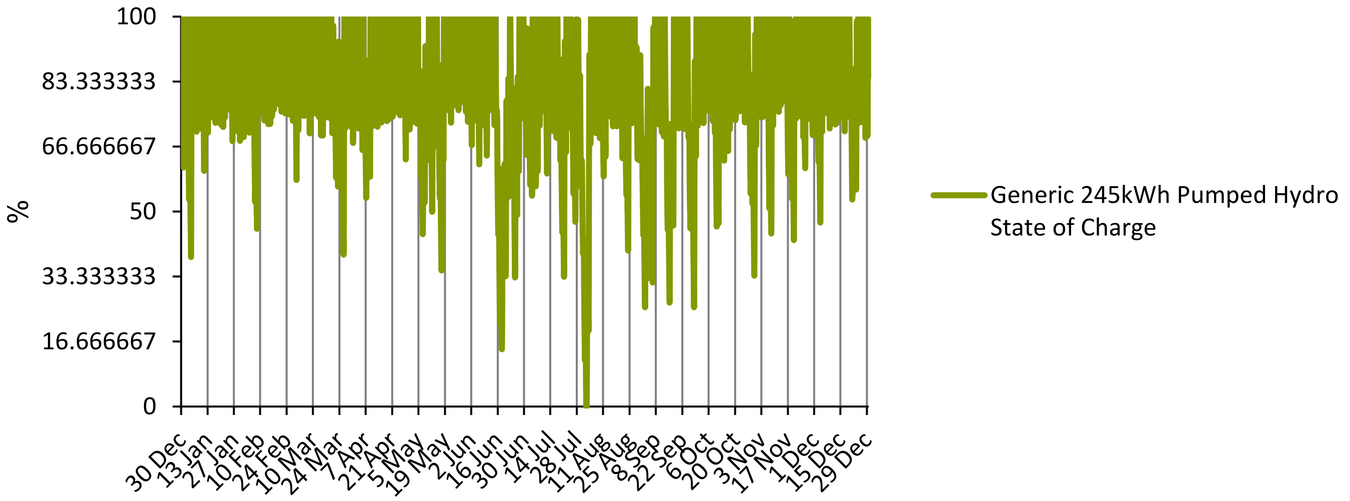
Time series charts:





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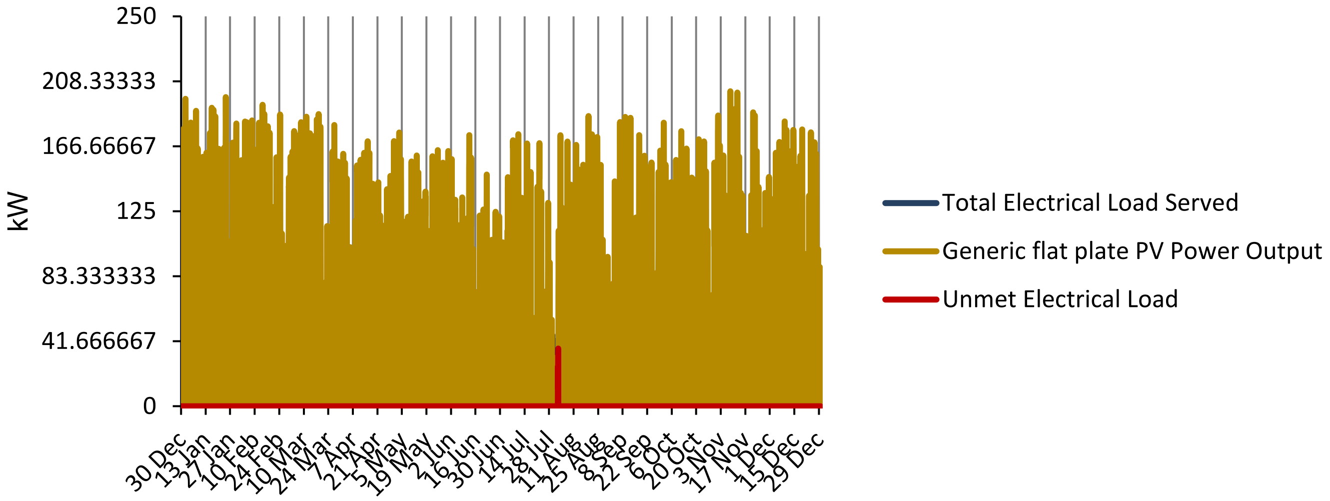

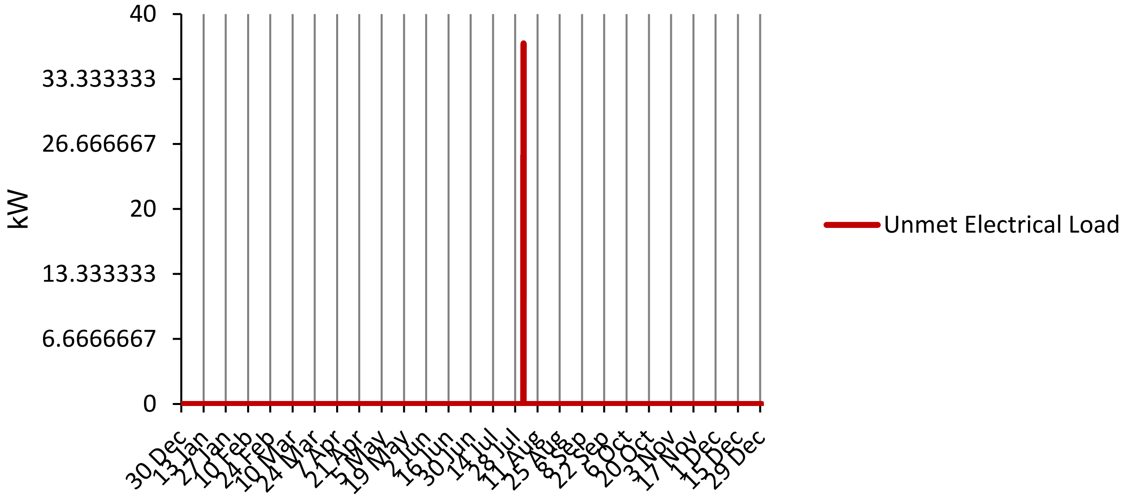

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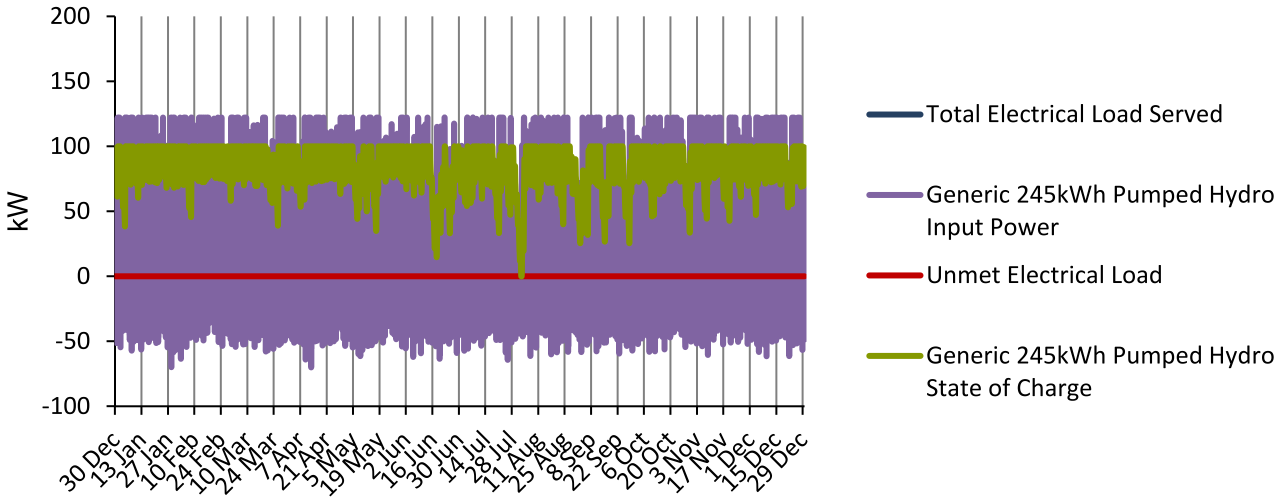

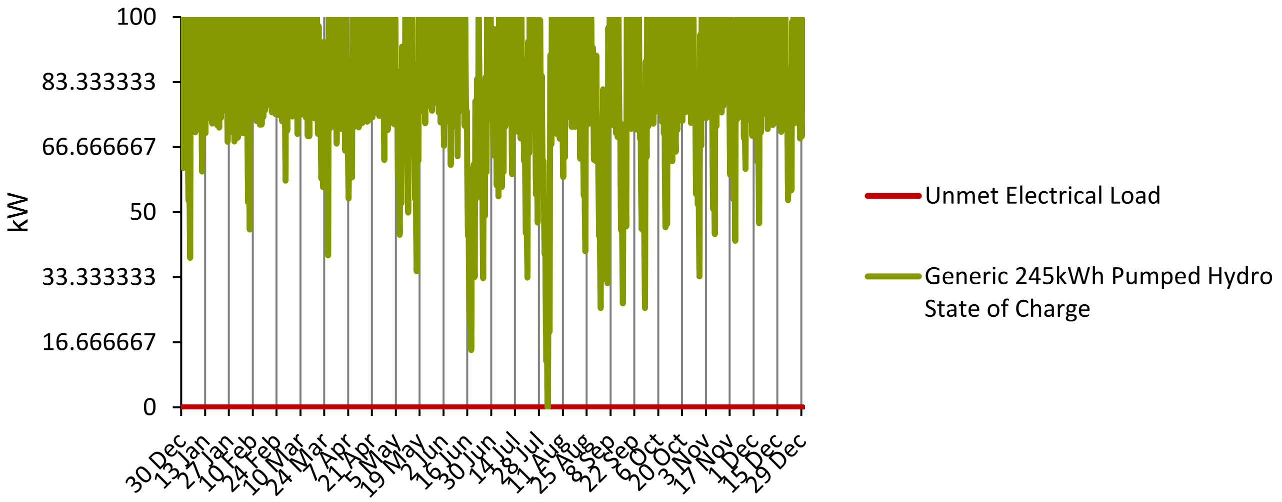

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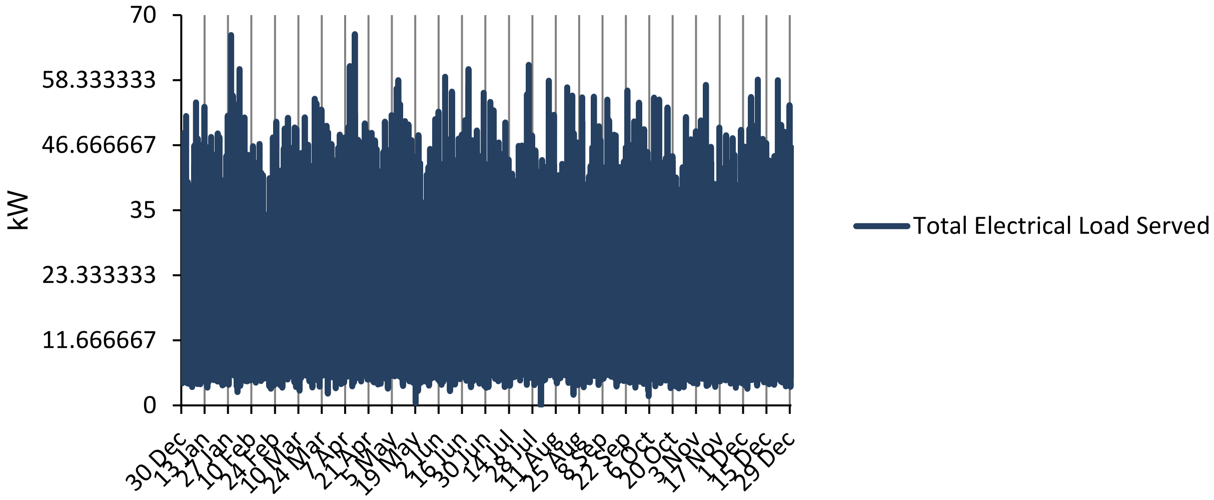

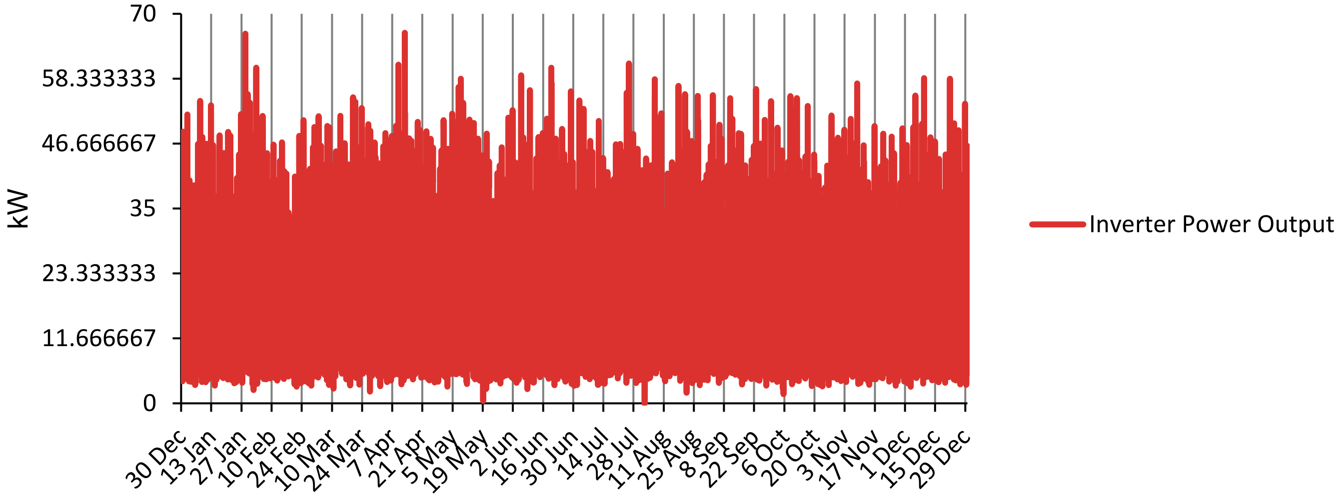

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