INTEGRATION OF SMART IoT ENERGY MONITORING SYSTEM FOR SOLAR-POWERED MICROGRID: CASE STUDY SIERRA LEONE

by

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CERTIFICATE OF APPROVAL

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DECLARATION OF CANDIDATES

This thesis paper **“Integration of Smart IoT Energy Monitoring System for Solar-Powered Microgrid: Case Study Sierra Leone”** under the supervision of **Prof. Dr. Khondokar Habibul Kabir** is hereby declared to be presented only to the Department of Electrical Engineering. Its entirety has not been submitted for the award of a degree or diploma anywhere.

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DEDICATION

This work is dedicated to our brother Abubakarr Sillah, Former President of ISC. His unwavering sacrifice for international students, epitomized by his expulsion from the university for standing in solidarity with the students at the Islamic University of Technology, serves as a beacon of courage and selflessness. His commitment to justice and advocacy inspires us to strive for positive change in our communities. May his resilience and dedication continue to ignite the flames of activism and compassion in all who encounter his story.

ABSTRACT

A smart IoT energy monitoring system for a solar-powered microgrid in Sierra Leone is implemented and presented in this study. Microgrids that are powered by solar energy have emerged as a promising approach to address the issues of consistent and sustainable energy availability in developing countries, especially in rural places[1]. For these microgrids to operate as best they can, however, effective resource management and monitoring are necessary. Here, we use Internet of Things (IoT) technology and Homer Pro software to create and install an advanced energy monitoring system. Homer Pro software is used for system design, optimization, and simulation, and it is integrated with Internet of Things (IoT) devices for data collecting, transfer, and analysis[2]. Real-time data on energy production, use, and storage is provided by the energy monitoring system. It also has an easy-to-use interface for controlling and monitoring in real-time. Users can monitor energy usage, spot inefficiencies, and optimize energy consumption thanks to the system's remote monitoring and control capabilities[3]. In this study, we examine viable substitutes for traditional power generating systems with the goal of delivering electricity in a cost-effective, dependable, and sustainable way. These substitutes include the utilization of solar renewable energy sources and less carbon-intensive technology. In addition, the study addresses the scalability, future prospects, and socioeconomic effects of smart IoT energy monitoring systems in relation to sustainable development[4]. In summary, this study advances the use of IoT applications in energy systems and provides workable solutions to improve resilience, efficiency, and access to energy in Sierra Leone.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Acronyms

AC	alternating current
CLSG	Côte d'Ivoire-Liberia-Sierra Leone-Guinea
COs	Course Outcomes
DC	direct current
GHI	Global Horizontal irradiance
GWh	Gigawatt hours
HEMS	Home Energy Management Systems
IoT	Internet of Things
IUT	Islamic University of Technology
LCOE	Levelized Cost of Energy
MW	Megewhatt
MWh	Megewhatt hour
NGOs	Non- Governments Organizations
NPC	Net Present Cost
OBE	Outcome Based Education
POs	Program Outcomes
PV	Photovoltaic
RL	resistance
SHS	Solar Home Systems
SoC	State of Charge

CHAPTER 1

INTRODUCTION

1.1 Background

Like many other sub-Saharan African nations, Sierra Leone has formidable obstacles in supplying its people with inexpensive, dependable power. Sierra Leone, home to roughly 7.9 million people, only over 26% of the population has access to electricity, making it one of the least electrified countries in the world. [5]. The primary source of electricity generation in Sierra Leone's energy sector is a significant reliance on fossil fuels, specifically diesel generators[6]. Due to the high cost and environmental impact of the fuels used, many Sierra Leoneans find it impossible to afford the country's high electricity bills. In addition, the sporadic nature of diesel generation frequently causes interruptions and power outages, impeding the advancement of the economy and standard of living.

The potential of renewable energy sources to alleviate Sierra Leone's energy problems has come to light more and more in recent years. Sierra Leone's abundant sunshine has made solar energy in particular seem like a possible answer. Microgrids powered by solar energy have gained popularity as a competitive substitute for conventional grid extensions because they can supply off-grid and isolated populations with inexpensive, clean electricity[7].

However, maintaining the dependability, effectiveness, and long-term sustainability of solar-powered microgrids depends heavily on efficient management and close observation. Real-time monitoring systems are essential for maximizing energy generation and use, spotting abnormalities and defects, and enhancing grid operation as a whole.

This research project aims to create and deploy an IoT-based energy monitoring system for a solar-powered microgrid in Sierra Leone. The system will enable real-time monitoring and management of electricity generation, usage, and storage, enhancing the microgrid's reliability and efficiency. By analyzing energy usage trends, it will improve resource allocation and energy distribution decisions. Additionally, remote monitoring and control will boost the microgrid's efficiency and reliability, contributing to sustainable energy access in the region. This project demonstrates the effectiveness of IoT solutions in addressing energy challenges in off-grid communities, paving the way for broader adoption of similar technologies.

1.2 Research Objectives

The main goal of this project is to develop and implement a smart Internet of things energy monitoring system specifically designed for a solar-powered microgrid in Sierra Leone. Several ancillary goals have been established in the pursuit of this objective[8]. In order to collect data, these include building strong sensor networks, providing user-friendly interfaces for real-time monitoring, and making sure the system is sustainable and scalable in the local environment.

- Assess the current energy infrastructure and challenges in Sierra Leone[9].
- Explore existing energy monitoring technologies and their applicability to the context of Sierra Leone
- Develop a framework for the Smart IoT Energy Monitoring System tailored to the specific needs and conditions of Sierra Leone
- We aim to develop a customized solar-powered microgrid with smart IoT energy monitoring system tailored to Sierra Leone's energy sector, considering factors like scalability, reliability, and cost-effectiveness.
- Examine the efficiency and efficacy of the system in place for enhancing grid reliability and energy management in a microgrid driven by solar energy.

1.3 Motivation

Integrating a smart IoT energy monitoring system into solar-based microgrids in Sierra Leone presents a transformative opportunity to enhance energy management and sustainability. Sierra Leone faces significant challenges in achieving reliable and affordable energy access, with the majority of its population lacking connection to the national grid. By leveraging IoT technology, real-time monitoring, and data analytics, this system can optimize solar energy production and distribution, reducing inefficiencies and downtime.

Such an advanced monitoring solution will enable proactive maintenance, informed decision-making, and efficient energy utilization, ultimately fostering energy resilience in remote and underserved communities. Moreover, it supports Sierra Leone's commitment to renewable energy and environmental sustainability by maximizing the potential of solar power. This case study aims to demonstrate how smart IoT integration can revolutionize energy infrastructure in developing regions, providing a scalable model for similar contexts globally, thereby contributing to economic growth and improved

1.4 Organization of the Thesis

Chapter 1: Introduction
Chapter 2: Literature Review
Chapter 3: Methodology
Chapter 4: Solar Microgrid Development Using Homer-Pro
Chapter 5: Results and Discussion
Chapter 6: Conclusion and Future Work

1.5 Sierra Leone Energy Capacity

The overall installed capacity is approximately 150 MW, Hydropower: 56 MW Thermal (diesel and heavy fuel oil) at 63 MW, Solar: Around 5 MW, Biomass: Roughly 23 MW from pilot projects[10].

Table 1 Electricity generation (GWh) 2021

Generation in 2021	GWh	%
Non- Renewable	**80**	**25**
Renewable	**224**	**75**
Hydro and Marine	228	70
Solar	6	2
Wind	0	0
Bioenergy	9	3
Geothermal	0	0
Total	**324**	**100**

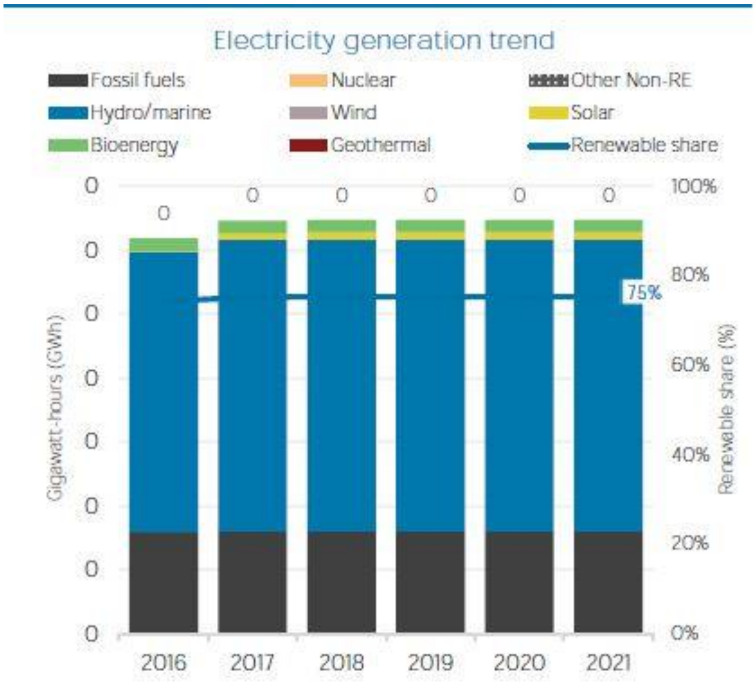


Figure 1 Electricity Generation Trend

1.6 Sierra Leone's Electricity Situation

Two heavy fuel power plants situated on barges off the coast of Freetown, known as Karpowership, are currently Sierra Leone's main source of electricity. Together, they can supply 65 MW of energy during the dry season and 23 MW during the rainy season to the country's capital, Freetown. The state-owned Bumbuna hydroelectric project, which produces 50 MW during the rainy season and 8 MW during the dry season[11], is the other main source of energy. Roughly 90% of the energy generated by the Bumbuna hydroelectric dam reaches Freetown, with the shield wires supplying power to the northern city of Makeni, which is situated along the 161 kV line. Charlotte and Bankasoka, two smaller hydroelectric facilities, generate 2 MW and 2.2 MW, respectively.

However, because of the low water levels during the dry season, many smaller hydropower facilities are compelled to shut down completely. The company Sunbird Bioenergy uses the waste from its sugarcane fields to make bio-ethanol, of which up to 15 MW is fed into the national grid. This results in 32 MW of power being produced. Furthermore, through a power purchase agreement negotiated by the two nations, the regional interconnection TRANSCO CLSG 225 kV line, which connects Cote d'Ivoire to Sierra Leone, started supplying 27 MW to Sierra Leone in December 2021. Right now, Freetown, Bo, and Kenema are the recipients of this Power.

Electricity will be provided to twenty-nine rural settlements located 3 km along the CLSG interconnection transmission line. This will enhance the quality of life for the larger population residing in these communities. The nation's existing generation facilities are shown in Table 2. In 2021, the combined electricity generated by thermal plants, hydropower, fuel oil, and solar power plants was 229,844,780, 325,895,860, and 4,500,000, respectively. As seen in Figure 2, this corresponds to 41% of hydropower, 58% of fuel oil thermal plants, and 1% of solar power. Installed generation capacity from fuel oil thermal plants climbed from 43.4 MW in 2015 to 179.4 MW in 2021, a 313.36% increase, and from renewable sources (solar and hydro) it increased from 50 MW in 2015 to 66.52 MW in 2021, a 33.04% rise.

The 65 MW from the Karpowership are included in this increase in generation. As shown in Table 3, the total gross electricity output grew by 123.13% from 247,047.287 MWh in 2015 to 551,240.640 MWh in 2021[12]. The public electricity supply in Sierra Leone is unstable and unreliable, and the country's domestic demand is still mostly unfulfilled. The limited involvement of the private sector and insufficient funding for energy-related investments are contributing factors to these issues. Inadequate planning and relevant legislation to guarantee a sustainable supply of electricity are further issues.

Table 2 Projected Production from Diverse Sources by 2030

Generation Technology	**Projected Generation in 2030 (MW)**
Thermal	90
Large- and Small-Scale Hydro	560
Renewable	120
Total	770

CHAPTER 2

LITERATUE REVIEW

2.1 Overview of Solar- Powered Microgrid

In areas where standard power grids are not easily accessible, solar-powered microgrids are becoming more and more acknowledged as a feasible option for supplying dependable and sustainable electricity. A microgrid is a small-scale energy system that may function both separately and in tandem with the larger power grid. Microgrids that run on solar power use photovoltaic (PV) panels to collect sunlight and turn it into electrical power. This section explores the foundational elements, advantages, difficulties, and uses of microgrids fueled by solar energy.

In order to improve energy access and sustainability in underdeveloped nations like Sierra Leone, the integration of smart IoT energy monitoring systems within solar-based microgrids are a rapidly expanding topic. This chapter examines the body of research on solar microgrids, IoT in energy management, and their application in related fields. In order to support the current study, it also reveals gaps and possible areas for improvement.

2.2 IoT in Energy Monitoring Systems

IoT deployment in energy monitoring systems has demonstrated great promise for increasing dependability and efficiency. IoT devices make it easier to monitor and control energy systems continuously since they have sensors and real-time data transmission capabilities. To improve energy usage and save operating costs, for example, IoT-based systems have been effectively used in urban contexts.

Existing Initiatives:

- Smart Grid Solutions: In India, smart grids incorporating IoT have demonstrated significant improvements in energy distribution efficiency and grid stability. These systems utilize real-time data to predict and manage energy demand, reducing wastage and ensuring a balanced supply.

- Solshare Bangladesh: Monitors everyone's energy usage and distributes it in a way that ensures everyone receives their fair share of solar energy.
- Home Energy Management Systems (HEMS): North America dominates the HEMS market, Europe is expected to second, Asia Pacific is anticipated to grow faster, thus there is a prospect for Africa to develop in HEMS[13], and Sierra Leone can leverage the opportunity to grow in this aspect

Existing Initiatives:

- **African Solar Designs:** Projects in Kenya and Tanzania have successfully deployed solar microgrids, providing energy to remote communities and significantly improving living standards.
- **Bangladesh's Solar Home Systems (SHS):** This initiative has installed over 4 million SHS units, leveraging solar energy to power homes in rural areas and showcasing the potential of decentralized solar solution.

2.3 Solar-Based Microgrid

A small-scale energy system that integrates solar power, energy storage (such as batteries), and often additional renewable energy sources (such as wind or hydroelectricity) is called a solar microgrid. Unlike traditional centralized power grids, which distribute electricity from large power plants over long distances, solar microgrids operate on a smaller scale and are typically designed to support specific communities, buildings, or even individual residences[14].

2.3.1 How do Solar Microgrid work

High-end solar panels, particularly monocrystalline ones with efficiencies exceeding 24%, harness solar energy, which is then converted into direct current (DC) electricity via photovoltaic cells. This DC electricity is managed by a solar charge controller, which ensures the voltage and current are at appropriate levels to protect the microgrid's hardware. The electricity generated by the solar panels is directed to a combiner box, which reduces energy loss, consolidates the energy into a single link, and protects other components of the system. Additionally, the combiner box enables performance monitoring of the microgrid[14]. The electricity from the solar panels is sent to a combiner box, which serves several purposes. It reduces energy loss, consolidates the energy produced into a single link, and protects the system's other parts. Furthermore, the combiner box allows for microgrid performance monitoring.

An inverter is used to convert the DC electricity into alternating current (AC), which is necessary for most appliances and equipment, making the energy suitable for homes, businesses, and other facilities. Some solar microgrids also include battery storage systems to store excess energy for later use, enhancing energy independence, reducing reliance on the main grid, and ensuring electricity availability when solar production is low. Additionally, in some setups, excess energy can be fed back into the main grid, providing compensation or credits to the system owners.

To track energy consumption, meters are used to monitor the amount of energy leaving the inverter. These meters help in measuring usage and setting prices for individual users or the community. The electricity generated by the microgrid is distributed to end users, including homes, businesses, and other facilities, meeting their energy demands and powering appliances, machines, and other devices[15]. Many solar microgrids have the capability to connect to or disconnect from the main grid at any time, providing flexibility and enhancing resilience and reliability. This feature allows users to efficiently access power from either the main grid or the microgrid, depending on their needs. Overall, solar microgrids offer a robust solution for generating and managing energy, supporting sustainability, and improving energy security for various applications.

2.4 Integrating IoT with Solar-Based Microgrid

The efficiency and dependability of solar microgrids are increased when IoT technology is integrated with them. IoT enables predictive maintenance, automated system modifications based on data analytics, and real-time monitoring of energy output and consumption. The integration of smart IoT energy monitoring systems with solar-based microgrids holds significant potential for enhancing energy access and sustainability in Sierra Leone. While existing initiatives and research provide a strong foundation, our study is tailored to the specific context of Sierra Leone, which is necessary.

2.5 Case Studies in Sierra Leone

There is a limited literature specifically focusing on the integration of IoT with solar microgrids in Sierra Leone. However analogous initiatives in other developing regions provide valuable insights. Off-grid solar systems in West Africa Projects in Ghana and Nigeria have demonstrated the feasibility and benefits of solar microgrids, suggesting a similar potential for Sierra Leone.

By 2018, there were reportedly 55 microgrids, with hopes to grow many more. Reports indicate that these microgrids are often smaller, with capacities as high as 5.5 kW. Sierra Leone's first commercial solar plant started in 2022 with a 5 MW capacity, with a planned expansion to 25 MW. The plant installed approximately 9 MW of solar capacity[16], a huge increase from 4 MW in 2021.

Key projects include:

1. Planet Solar Project**:** Spearheaded by Planet One Group and Frontier Energy, this 50 MW solar project has secured $52 million in financing and is expected to increase the country's installed capacity by 30%.
2. PowerGen Mini-Grids**:** PowerGen Renewable Energy has implemented mini-grids in rural communities, providing a total of 150 kW and benefiting households, healthcare facilities, and schools. This project aims to expand to 16 more communities, improving access to clean energy for 12,500 new connections.
3. Boama 1 Solar PV Plant: It is Sierra Leone's first solar-powered independent power project; this 5 MW plant is the first stage of a 25 MW project. The goal of this project is to lower electricity prices while diversifying the nation's energy source.

These projects highlight Sierra Leone’s ongoing efforts to enhance its energy infrastructure and increase the share of renewable energy in its grid.

CHAPTER 3

METHODOLOGY

3.1 Research Design

This chapter details the research methodology for investigating the integration of a smart IoT energy monitoring system in a solar-based microgrid in Sierra Leone. The methodology encompasses the design, implementation, and evaluation of the system, incorporating a review of existing initiatives, identification of improvement areas, and application of relevant mathematical models and tools[17]. The research employs a mixed-methods approach, combining qualitative and quantitative data collection and analysis, to achieve a comprehensive understanding of IoT integration in solar-based microgrids within the specific context of Sierra Leone.

3.2 Data Collection

We deployed a pilot IoT energy monitoring system in a selected microgrid and used the Blynk IoT platform to Gather current, voltage, power, and energy usage statistics in real time.

The data collected through the pilot implementation will include:

- Current I: measured in amperes, indicating the flow of electric charge.
- Voltage V: measured in volts, representing the electrical potential difference.
- Power P: measured in watts, calculated as the product of current and voltage ($P = IV$).
- Energy Consumption (kWh): measured in kilowatt-hours (kWh), representing the total energy consumed over time.

a) Analysis of similar projects in other regions, such as the IoT-enabled microgrids in India, Kenya, and the United States, to identify best practices and lessons learned.

b) Academic papers, industry reports, and IoT energy monitoring system case studies and solar microgrids

3.3 Smart IoT Meter's System Architecture

The system design and architecture of the proposed smart IoT energy monitoring system for a solar-based microgrid in Sierra Leone are based on a combination of hardware and software components. The design uses Proteus for simulation and includes a 20V solar panel integrated with smart IoT meters. The ESP32 WiFi module is used for data communication, and the Blynk IoT platform is employed for data visualization on LCDs, mobile apps, and desktop web interfaces. The architecture ensures real-time data collection, processing, and visualization.

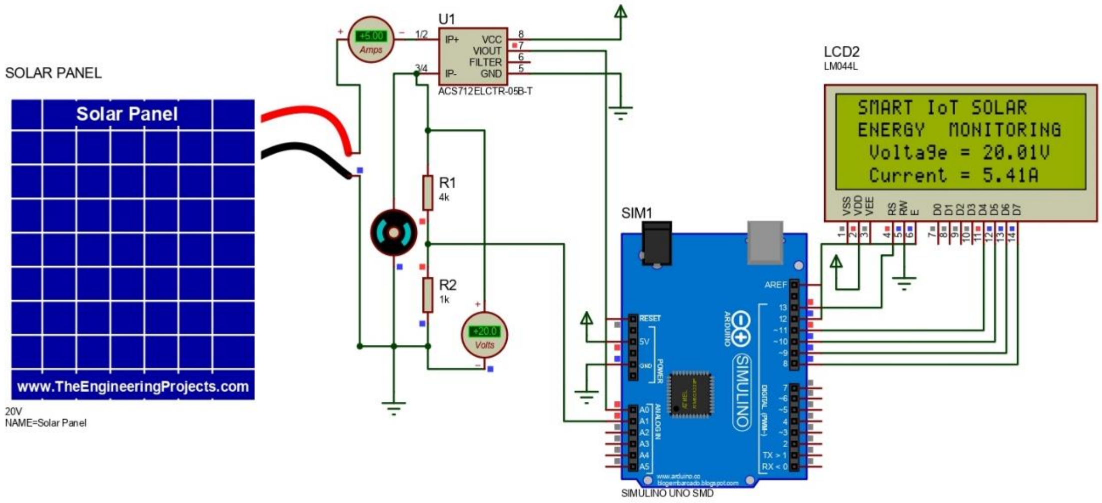


Figure 2 Solar Microgrid with smart IoT meter proteus simulation

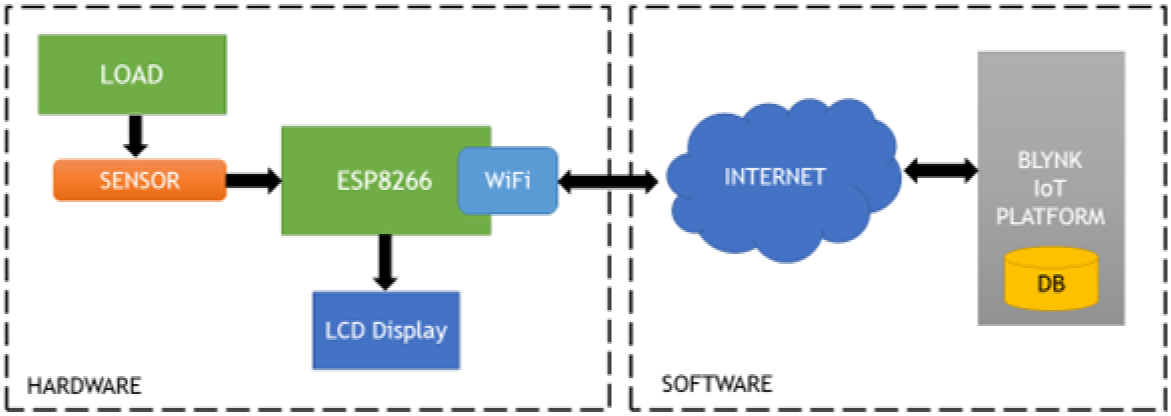


Figure 3 System Block diagram

3.4 Components Used

In this project, we constructed our own smart IoT energy meter using an ESP32, and we tracked data using the Blynk app. You must go to the meter reading room in order to take readings due to the current level of technology. Therefore, monitoring and controlling your electricity consumption is a tedious task [18]. We can use the Internet of Things to automate this. By automating distant data collecting, the Internet of Things reduces costs and saves time. In recent years, the Smart Energy Meter has garnered significant praise from people all over the world. We chose the voltage and current sensors in order to measure the voltage and current and, as a result, determine the power consumption and total power used.

SCT-013 is currently the best available sensor as of right now. This SCT-013 Non-Invasive AC Current Sensor Split Core Type Clamp Meter Sensor measures AC current up to 100 amperes. Likewise, the best voltage sensor is the AC Voltage Sensor Module ZMPT101B. The ZMPT101B AC Voltage Sensor functions effectively when a voltage transformer is used to precisely measure the AC voltage. The ZMPT101B voltage sensor with the SCT-013 current sensor can measure every parameter required for an energy meter. The ZMPT101B voltage sensor and SCT-013 current sensor will be interfaced with the ESP32 Wi-Fi module [18]. The Blynk application will then receive the data from these sensors. It will display the power, voltage, current, and total units consumed in kWh on the Blynk Application Dashboard.
Summary of the components and functionalities Includes:

i. ESP32 Wi-Fi Module**:** A low-power microcontroller with integrated Wi-Fi and Bluetooth capabilities, used for wireless data transmission.

Figure 4 ESP 32 Wi-Fi Module

ii. 2X04 I2C LCD Display**:** An LCD display that uses the I2C protocol for easy integration and real-time data display.

iii. Resistors and capacitors are used for voltage regulation, signal conditioning, and other essential circuit functions.

iv. Breadboard and wires**:** for prototyping and connecting various components.

v. Bulbs: Used as a load to simulate energy consumption within the microgrid.

vi. ZMPT101B AC Single Phase voltage sensor module utilizes a high precision voltage transformer, allowing for accurate measurement of AC voltage using an ESP32 or Arduino. It features a multi-turn trim potentiometer for calibration and modification.

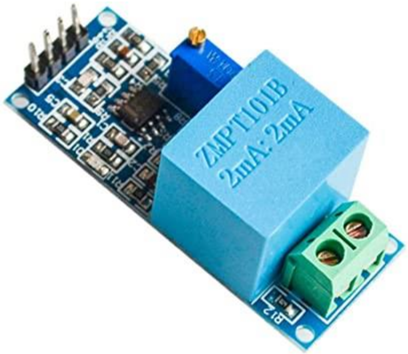


Figure 5 ZMPT101B Voltage Sensor

Specifications:

- One is able to measure voltage up to 250 volts.
- lightweight and equipped with a micro-precision voltage transformer on board
- Superior accuracy on-board op-amp circuit
- Working temperature range: 40°C to 70°C
- Voltage range for the supply: 5 to 30 volts.

vii. SCT-013 Current Sensor is a non-invasive AC Current Sensor that measures AC current up to 100 amperes, enabling the measurement of whole building electricity consumption without high voltage electrical work.

Figure 6 SCT-013 Current Sensor

Specifications:

- Current Input: 0-30A AC
- 2-3% non-linearity
- Dielectric Strength
- 1000V AC/1 min 5 mA (between shell and output)
- Resistance Level: Level B
- Ratio of Turn: 1800: 1
- Built-in sampling resistance (RL) : 62 Ω;
- Work Temperature: -25 °C~+70 °C
- Output Signal: DC 0–1 V

3.5 Design Hardware Prototype

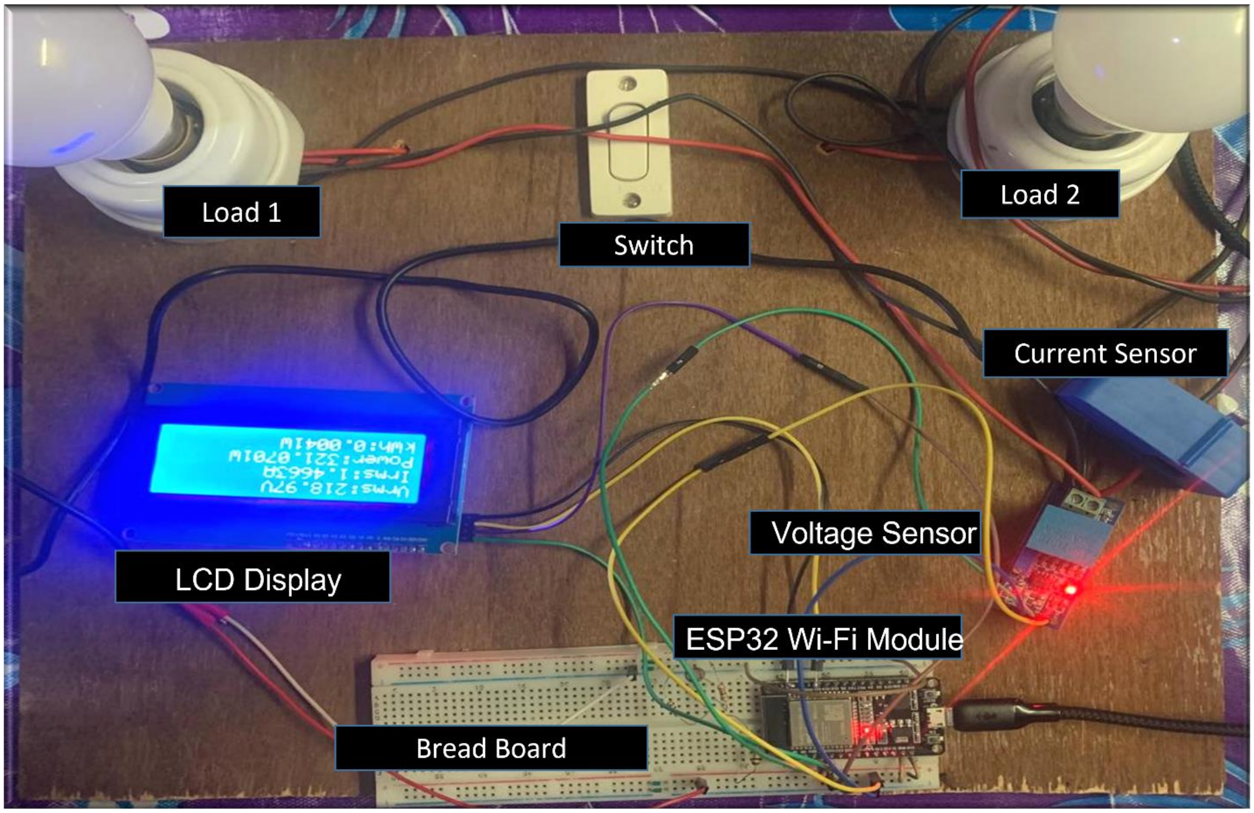


Figure 7 Smart IoT Meter Prototype

We will monitor the ESP32/SCT-013 ZMPT101B/energy meter data on the Blynk application, thus we will need a 20x4 LCD display to watch the data. linked the ESP32 D13, D12, D14, D27, D26, and D25 pins to pins 4, 6, 11, 12, 13, and 14 of the LCD. Additionally, we link pins 1, 5, 16 of the LCD to GND and pin 2 of the LCD to 5V VCC. the LCD's Pin 3 10K potentiometer to change the contrast. The lights act as loads by being connected to a power source and turning on a switch.

3.6 Mathematical Model

Solar Energy Prediction Model

Using historical weather data and real-time solar irradiance measurements, we apply a regression model to predict solar energy generation[12].

$$E(t) = a + b * I(t) + C * T(t) + \in$$

- $\mathrm{E(t)}$ = energy generated at time t
- $\mathrm{I(t)}$ = solar irradiance at time t
- $\mathrm{T(t)}$ = temperature at time t
- a, b, c = model coefficients
- ϵ = error term

Battery State of Charge (SoC) Model[19].

The SoC of battery storage is estimated using a Coulomb counting method:

$$SoC(t) = SoC(t-1) + \frac{1}{c}\int_{t-1}^{t} I_{bat}(t)\,dt$$

Where:

- $SoC(t)$ = state of charge at time t
- C = battery capacity
- $I_{bat}(t)$ = battery current at a time

Load Balancing Model

$$L(t) = \sum_{i=1}^{n} \left(\frac{p_i(t)}{Bi(t)}\right)$$

Where:

- $L(t)$ = load at time t
- $p_i(t)$ = power consumed by the device i at time t
- $Bi(t)$ = battery level of device i at time t
- $n\ is\ the\ number\ of\ devices$

Energy Balanced Equation

$$E_{generated} = E_{consumed} + E_{stored} + E_{loss}$$

Where $E_{generated}$ is the energy produced by the solar panels, $E_{consumed}$ is the energy used by consumers, E_{stored} is the energy stored in batteries, and E_{loss} represents system losses

This methodology offers a thorough framework for combining solar-powered microgrids in Sierra Leone with intelligent Internet of Things energy monitoring devices[20]. Through the utilization of current programs, sophisticated data examination, and mathematical simulation, the suggested framework seeks to optimize energy handling, boost dependability, and facilitate sustainable growth. Subsequent investigations will concentrate on improving the models and extending the system to additional areas.

3.7 Importance of Smart IoT Energy Meter

- You can monitor energy usage at comfort anywhere
- It promotes energy-efficient habits, and leads to cost savings for consumers and utilities.
- Automated data collection, facilitates quick responses, decreasing downtime.
- Accurate billing, minimize disagreements, guarantee fair invoicing, boost customer happiness
- Despite initial costs, smart meters offer sustained benefits.

CHAPTER 4

HOMER-PRO MICROGRID

4.1 Solar Microgrids Using HOMER Pro Optimization

This chapter examines a proposed microgrid In Kambia 3, a community within Kambia Town, Sierra Leone (9°7.1'N, 12°56.3'W), we are embarking on the design and implementation of a solar microgrid using HOMER Pro. This project aims to provide reliable and sustainable energy to 150 households. The proposed system has a Total Net Present Cost (NPC) of $546,261.50 and a Levelized Cost of Energy (LCOE) of $0.700 per kWh[21]romises to enhance the quality of life for residents by ensuring consistent power supply but also leverages the region's ample solar resources to promote environmental sustainability.

Solar Microgrid Using HOMER Pro Optimization

Figure 8 Kambia map

Table 3 Microgrid Specification

Component	Name	Size	Unit
PV	CanadianSolar All-Black CS6K-290MS	139	kW
Storage	Generic 1kWh Lead Acid	154	strings
System converter	System Converter	28.0	kW
Dispatch strategy	HOMER Cycle Charging		

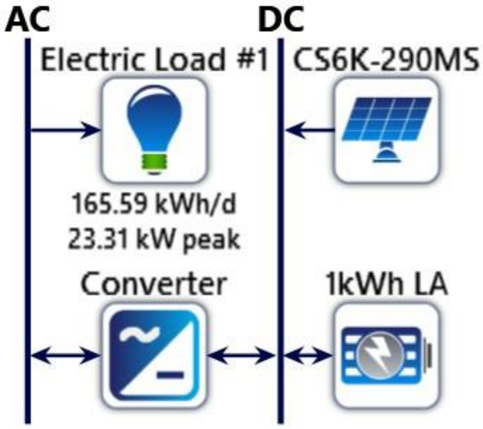


Figure 9 Homer-Pro Solar Microgrid Schematic

4.2 Electrical Summary

The designed solar microgrid for the Kambia 3 community demonstrates significant efficiency and capacity. With an annual production of 229,367 kWh exclusively from Canadian Solar All-Black CS6K-290MS panels, the system generates ample electricity. The community's total consumption stands at 60,401 kWh per year, resulting in an excess electricity production of 160,280 kWh annually. Despite this surplus, there is a minor unmet electric load of 40.3 kWh per year and a capacity shortage of 60.3 kWh per year[22]. This highlights the microgrid's robust performance in meeting the community's energy needs while providing a sustainable solution.

Table 4 Excess and Unmet

Quantity	**Value**	**Units**
Excess Electricity	160,280	kWh/yr.
Unmet Electric Load	40.3	kWh/yr.
Capacity Shortage	60.3	kWh/yr.

Table 5 Production Summary

Component	**Production (kWh/yr.)**	**%**
CanadianSolar All-Black CS6K-290MS	229,367	100
Total	**229,367**	**100**

Table 6 Consumption Summary

Component	**Consumption (kWh/yr.)**	**%**
AC Primary Load	60,401	100
DC Primary Load	0	0
Total	60,401	100

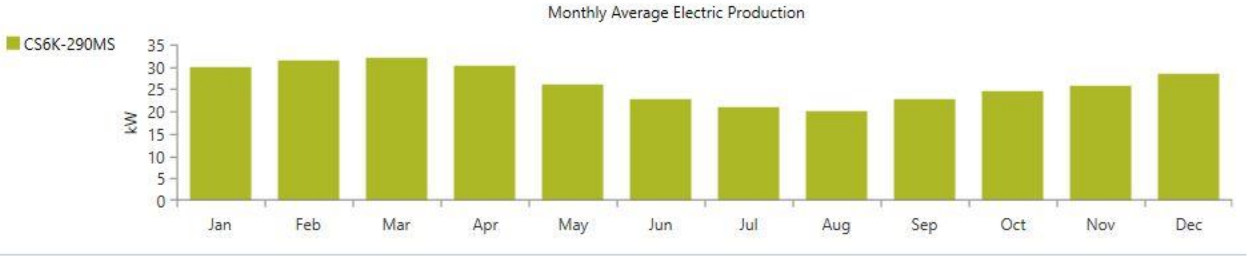


Figure 10 Monthly Average Electric Production

4.2.1 PV Power Output Summary

The solar microgrid for Kambia 3 is rated at 139 kW, with a mean output of 26.2 kW and a daily average output of 628 kWh. This results in a capacity factor of 18.9%, contributing to an annual total production of 229,367 kWh. The system's output ranges from a minimum of 0 kW to a maximum of 137 kW, reflecting its responsiveness to varying sunlight conditions[23]. With a PV penetration of 379% and 4,324 hours of operation per year, the microgrid efficiently meets energy demands at a levelized cost of $0.0764 per kWh, ensuring sustainable and cost-effective power for the community.

Quantity	Value	Units
Rated Capacity	139	kW
Mean Output	26.2	kW
Mean Output	628	kWh/d
Capacity Factor	18.9	%
Total Production	229,367	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	137	kW
PV Penetration	379	%
Hours of Operation	4,324	hrs/yr
Levelized Cost	0.0764	$/kWh

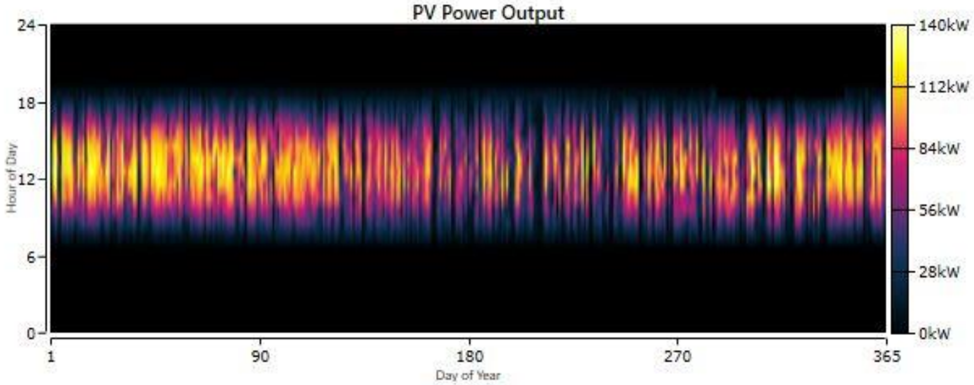


Figure 11 PV: CanadianSolar All-Black CS6K-290MS

4.2.2 System Converter Summary

The system converter for the Kambia 3 solar microgrid has a capacity of 28.0 kW and operates continuously throughout the year (8,760 hours). It maintains a mean output of 6.90 kW, with output ranging from 0 kW to a maximum of 23.3 kW, resulting in a capacity factor of 24.6%. Annually, the converter processes 62,270 kWh of energy input, delivering 60,401 kWh of usable energy output while experiencing 1,868 kWh of losses[24]. This efficient conversion process is critical in managing and optimizing the energy flow between the solar panels, batteries, and the community's load requirements.

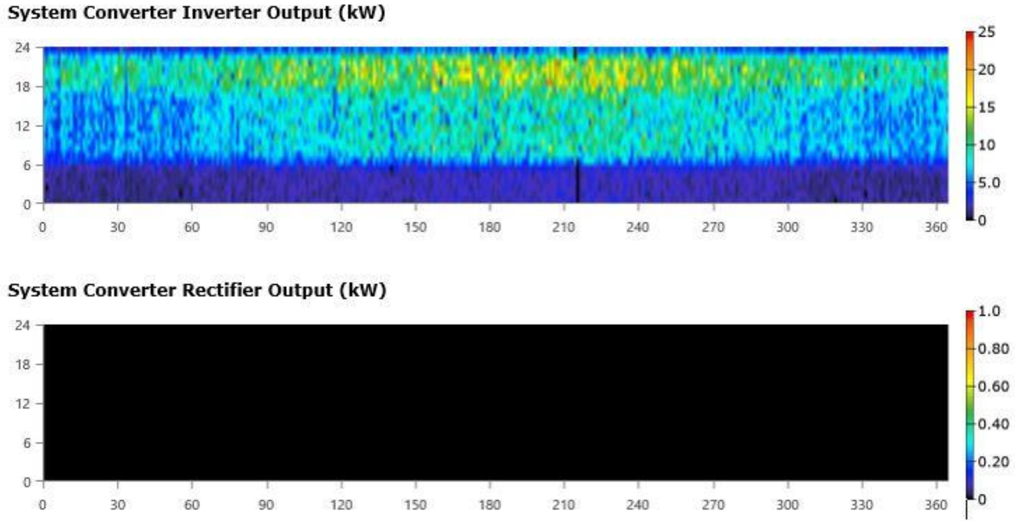


Figure 12 System Converter

4.2.3 Storage Summary: Generic 1kWh Lead Acid Batteries

The storage system for the Kambia 3 solar microgrid consists of 616 Generic 1kWh Lead Acid batteries configured in 154 parallel strings of 4 batteries each, with a bus voltage of 48.0V. This setup provides an autonomy of 53.6 hours and a nominal capacity of 616 kWh, with a usable capacity of 370 kWh. The system boasts a lifetime throughput of 492,800 kWh and an expected lifespan of 16 years[25]. Annually, it handles 34,339 kWh of energy in and 27,521 kWh out, with storage depletion at 56.0 kWh and losses at 6,874 kWh, resulting in an annual throughput of 30,769 kWh. The storage wear cost is $0.419 per kWh.

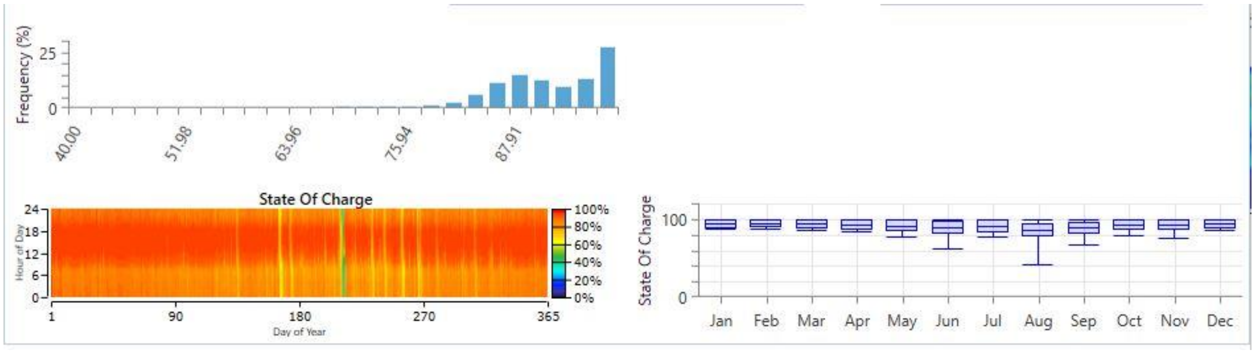
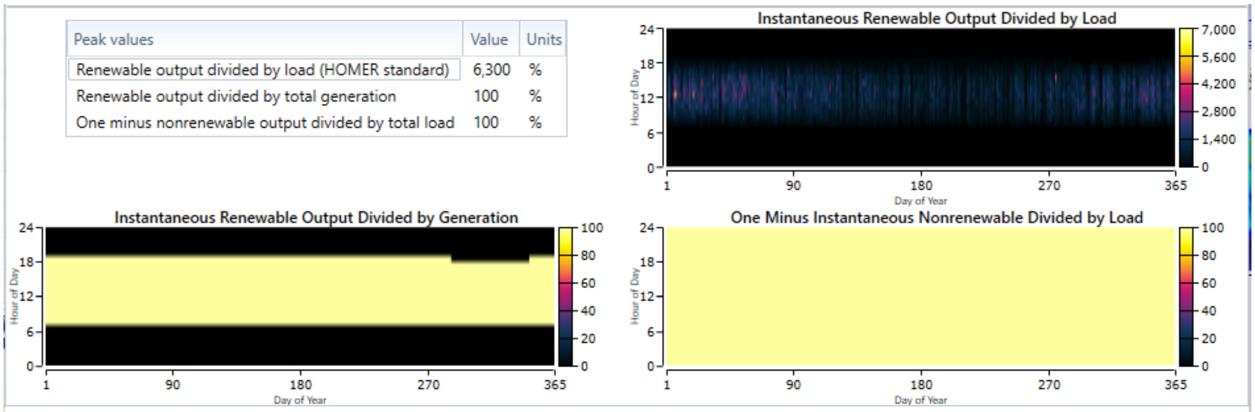


Figure 13 Storage Generic 1kWh Lead Acid Output

4.2.4 Renewable Penetration Summary

The microgrid exhibits impressive renewable energy penetration metrics. With a nominal renewable capacity comprising 100% of the total capacity and usable renewable capacity also at 100%, the system relies entirely on renewable sources. Total renewable production exceeds the community's load by 380%, ensuring ample supply[26]. All generated energy is from renewable sources, resulting in a 100% renewable generation rate. Standard measures indicate renewable output at 6,300% of the load. These figures underscore the microgrid's exceptional efficiency and its commitment to sustainable energy, eliminating reliance on nonrenewable sources entirely.



Peak values	Value	Units
Renewable output divided by load (HOMER standard)	6,300	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

Figure 14 Renewable Summary

4.3 Daily Load Summary

The daily load profile for the Kambia 3 community shows a distinct pattern of energy consumption throughout the day. The average daily energy consumption is 165.59 kWh, with an average power demand of 6.9 kW. The peak demand reaches 23.31 kW. The load factor, which indicates the efficiency of the energy use relative to the peak load, is 0.3. This pattern suggests moderate daytime energy usage[27], escalating to higher levels in the evening. The community's energy demand is entirely based on AC loads, as indicated in the data provided.

Figure 15 Daily Load Profile

4.3.1 Seasonal Load Summary

The seasonal load profile for Kambia 3 shows consistent daily energy demand variations throughout the year. Early morning hours (midnight to 5 AM) see low consumption around 1.6 to 2.4 kW. Demand increases significantly from 6 AM, peaking between 6 to 9 PM with values reaching up to 14.4 kW in August. The load then tapers off towards late evening. Overall, energy demand is higher during the day and evening[28], particularly in the warmer months (May to August), reflecting typical residential and community usage patterns.

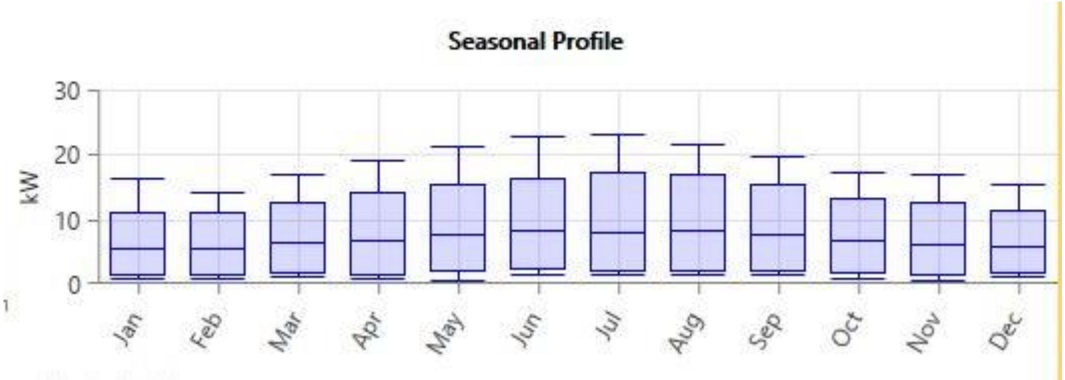


Figure 16 Seasonal Profile

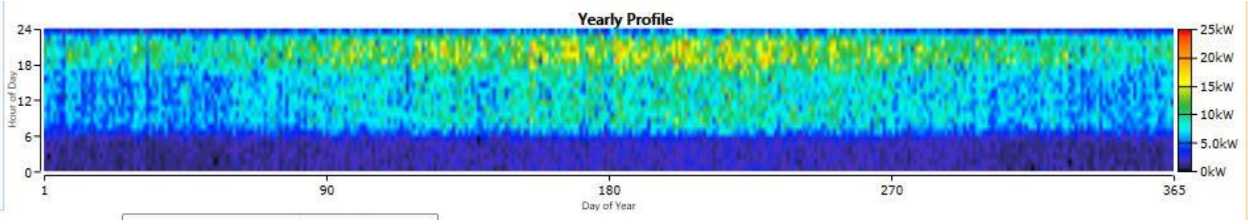


Figure 17 Year Load Profile

4.4 Cost and Economic Analysis Summary

The economic analysis of the solar microgrid system for Kambia 3 reveals a Total Net Present Cost (NPC) of $546,261.50. The system includes a 28.0 kW converter, 139 kW of Canadian Solar All-Black CS6K-290MS panels, and 154 strings of Generic 1kWh Lead Acid batteries, operating under HOMER Cycle Charging[29]. The Levelized Cost of Energy (LCOE) is calculated at $0.6996 per kWh, indicating the cost-efficiency of the system over its lifespan. The annual operating cost amounts to $15,183.09, reflecting the ongoing expenses required to maintain and operate the microgrid.

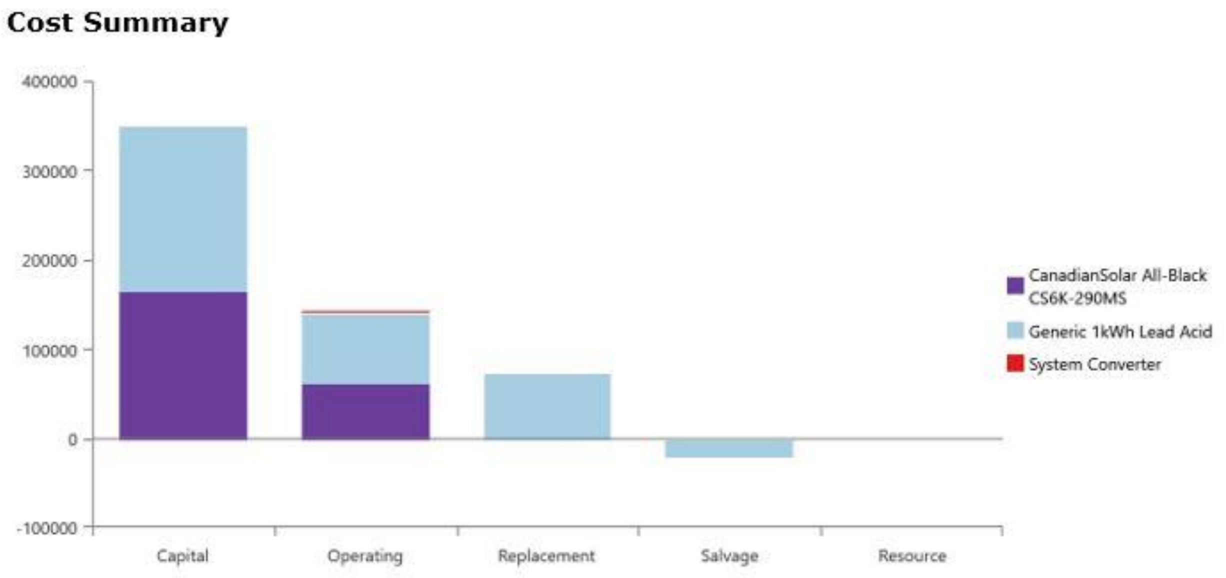


Figure 18 Cost Summary

Table 7 Net Present Cost

Name	Capital	Operating	Replacement	Salvage	Resource	Total
CanadianSolar All-Black CS6K-290MS	$164,790	$61,748	$0.00	$0.00	$0.00	$226,538
Generic1kWh Lead Acid	$184,800	$79,634	$73,982	$19,437	$0.00	$318,979
System Converter	$392.26	$217.32	$166.42	-$31.32	$0.00	$744.68
System	$349,982	$141,599	$74,149	$19,468	$0.00	$546,261

Table 8 Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
CanadianSolar All-Black CS6K-290MS	$12,747	$4,777	$0.00	$0.00	$0.00	$17,524
Generic1kWh Lead Acid	$14,295	$6,160	$5,723	-$1,504	$0.00	$24,674
System Converter	$30.34	$16.81	$12.87	-$2.42	$0.00	$57.60
System	$27,073	$10,953	$5,736	-$1,506	$0.00	$42,256

4.5 Cash Flow Analysis

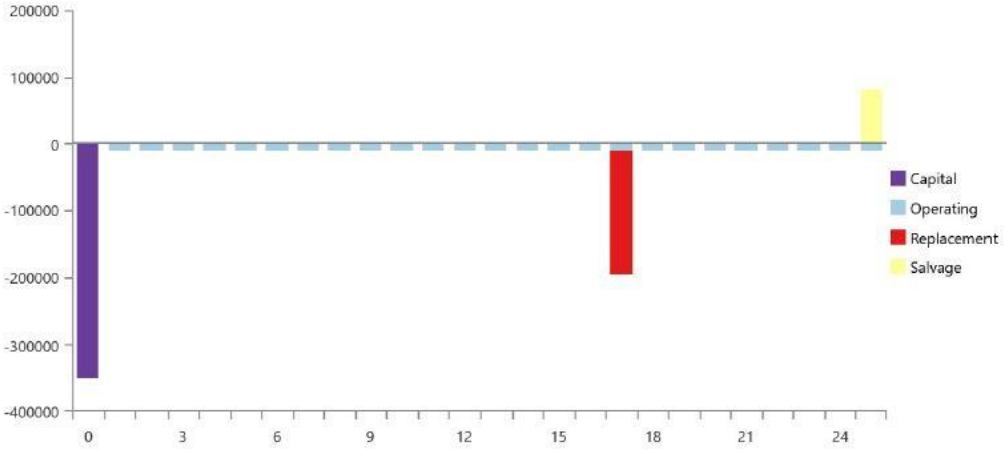


Figure 19 Cash flow by cost type

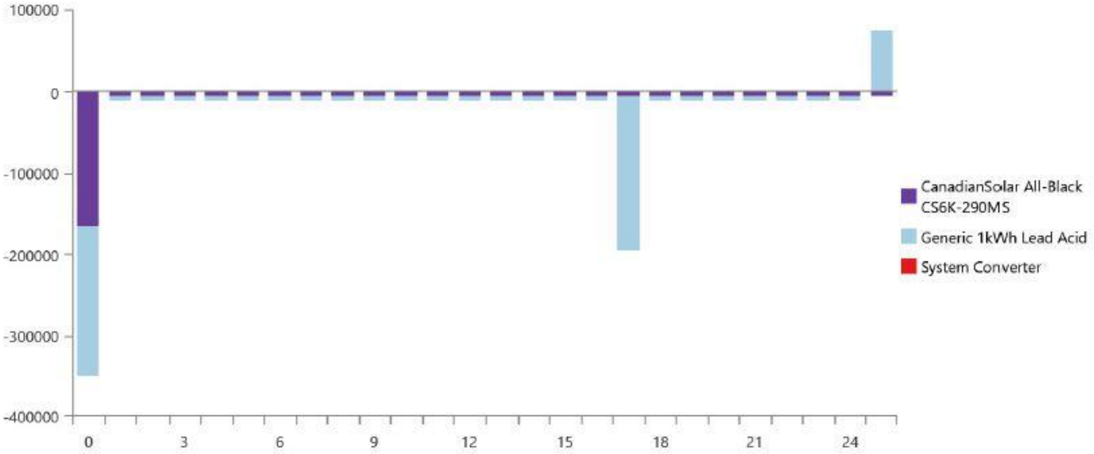


Figure 20 Cash flow by component

The cash flow analysis evaluates three components: CanadianSolar All-Black CS6K-290MS, Generic 1kWh Lead Acid, and System Converter. The nominal total capital cost is $349,982 with consistent monthly operating expenses, totaling $10,953 each month. The discounted cash flow reveals a gradual decrease in operating expenses over time, with significant future cost reductions in Generic 1kWh Lead Acid due to replacement costs and salvage values. CanadianSolar maintains steady but decreasing operating costs, while the System Converter shows minimal impact. The overall discounted total presents a more efficient financial picture over time, resulting in a net positive future cash flow of $16,845.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Data Recorded from the Smart IoT Energy Meter

In our study, we employed two 5-Watt bulbs as loads connected to a voltage and current sensor integrated with our custom-built smart IoT energy meter. The meter was designed to monitor and record voltage, current, power, and energy consumption (in kWh)[30]. The measurements were displayed on an LCD and could be accessed via the Blynk IoT app and web platform. The recorded values are as follows:

Table 9 Electricity Consumption

Consumption	**Values**
Voltage (Vrms)	4.60 V
Current (Irms)	0.2957 A
Power	1.3614 W
kWh	0.02919 kWh

```
Vrms: 4.60 V
Irms: 0.2957 A
Power: 1.3614 W
kWh: 0.02919 kWh
```

Figure 21 LCD display of Vrms, Irms, Power, kWh

5.1.1 Discussion

The measured voltage was 4.60 V, which is much lower than the expected mains voltage of 220-240 V. This suggests that the measurement might have been taken under reduced voltage conditions, possibly due to the connection method or an issue with the experimental setup. The recorded current was 0.2957 A, which aligns with the low voltage and the power rating of the bulbs. For a total of 10 W (two 5-Watt bulbs) at a higher nominal voltage, the current would proportionately increase. The calculated power was 1.3614 W, derived from the product of the recorded voltage and current $(P = v * I)$ Under normal voltage conditions, the power consumption should be closer to the bulbs' combined rating of 10 W, indicating that the lower power value reflects the reduced voltage during measurement[31]. The energy consumption recorded was 0.02919 kWh. Given that energy consumption is the integral of power over time, this value is reasonable for the recorded power level and suggests a brief measurement period.

5.2 Solar Global Horizontal irradiance[32] (GHI)

The Monthly Average Solar Global Horizontal Irradiance (GHI) data shows seasonal variation in solar energy availability. Peak daily radiation occurs from February to April, with values between 6.13 and 6.44 kWh/m²/day, while the lowest values are in July and August, at 4.34 and 4.06 kWh/m²/day, respectively[33]. The clearness index follows a similar trend, indicating higher clarity in early months and reduced clarity mid-year. The annual average GHI is 5.22 kWh/m²/day, reflecting overall solar energy potential for the year.

Table 10 Average Monthly Solar Global Horizontal irradiance (GHI)

Month	Clearness Index	Daily Radiation (kWh/m^2/day
January	0.622	5.600
February	0.635	6.130
March	0.626	6.440
April	0.600	6.300
May	0.529	5.480
June	0.465	4.740
July	0.424	4.340
August	0.391	4.060
September	0.444	4.560
October	0.488	4.760
November	0.538	4.890
December	0.603	5.280

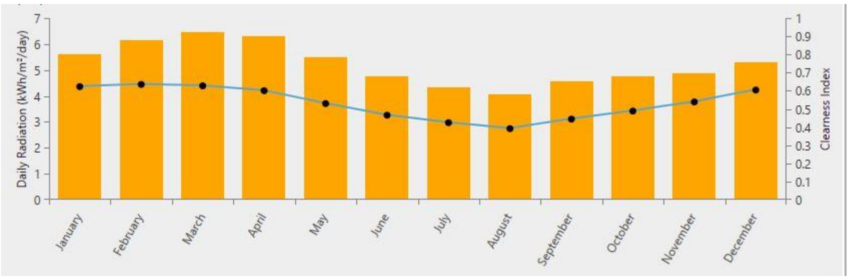


Figure 22 Solar GHI Radiation

5.3 Monthly Average Temperature

The Monthly Average Temperature data shows a variation throughout the year with an annual average of 25.27°C. The highest temperatures occur in February and March, both averaging around 27.57°C. The lowest temperatures are observed in July and August, at 23.61°C and 23.45°C, respectively[34]. The temperatures begin to decrease from May, reaching their lowest in mid-year, and gradually rise again towards December. This trend indicates a warmer climate in the early months of the year and cooler conditions during mid-year.

Table 11 Average Monthly Temperature

Month	Daily Temperature (°C)
January	26.670
February	27.560
March	27.570
April	27.020
May	25.430
June	24.450
July	23.610
August	23.450
September	23.970
October	24.360
November	24.280
December	24.920

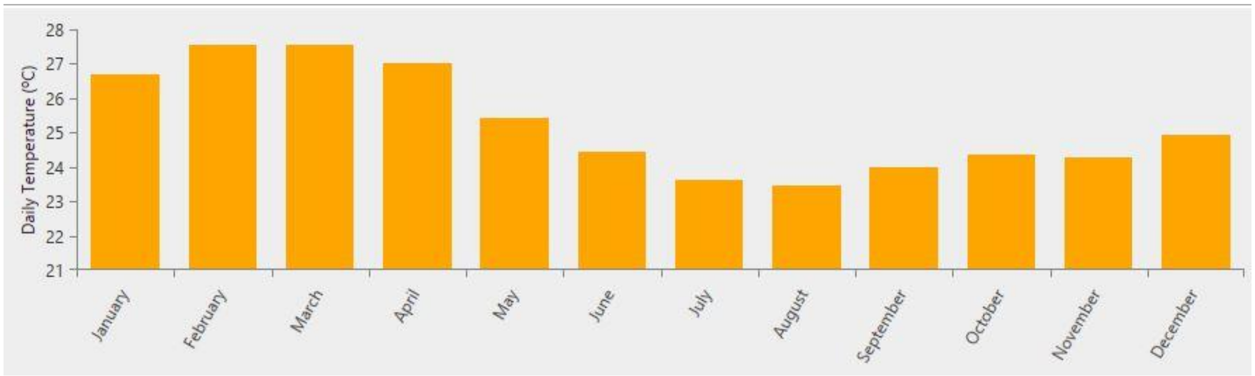


Figure 23 Daily Temperature (°C)

5.4 Demonstration of Outcome Based Education (OBE)

This section demonstrates Outcome Based Education (OBE) through various Course Outcomes (COs) linked to Program Outcomes (POs) in EEE 4700 & 4800 for Project and Thesis. The table highlights how each CO aligns with specific POs, addressing micro-grid inefficiencies, feasibility, ethical solutions, IoT tools, management plans, societal impacts, environmental sustainability, teamwork, communication, and ongoing education. This ensures a comprehensive, practical education framework

5.4.1 Course Outcomes

Table 12 Course Outcomes (Cos) addressed

COs	**CO Statement**	**POs**	**Put Tick (√)**
			EEE 4700
CO1	Identified micro-grid inefficiencies by reviewing renewable energy literature	PO2	(√)
CO2	Analyzed micro-grid feasibility, efficiency, and requirements for implementation.	PO4	(√)
CO3	Chose ethical solutions adhering to professional standards and codes.	PO8	(√)
CO4	Employed advanced IoT and monitoring tools for system design.	PO5	(√)
CO5	Developed a detailed management plan and budget for implementation.	PO11	(√)
CO6	Assessed impacts on health, safety, culture, and society	PO6	(√)
CO7	Evaluated environmental sustainability of the micro-grid solution	PO7	(√)
CO8	Created a solution addressing safety, cultural, and environmental factors.	PO3	(√)
CO9	Collaborated effectively within a team to develop the solution.	PO9	(√)
CO10	Produced comprehensive reports and presentations for project demonstration.	PO10	(√)
CO11	Emphasized ongoing education and involvement in professional societies.	PO12	(√)

5.4.2 Program Outcomes (POs)

Table 13 Program Outcomes (POs) Addressed

	Statement	**Different Aspects**	**Put Tick (√)**
PO3	**Design/development of solutions**: Develop an intelligent IoT system for solar micro-grid efficiency and dependability	Public health	
		Safety	
		Cultural	
		Societal	(√)
		Environmental	(√)
PO4	**Investigation:** Investigate integrating IoT in solar micro-grids for improved efficiency and sustainability	Design of experiments	(√)
		Analysis and interpretation of data	(√)
		Synthesis of information	(√)
PO6	**The engineer and society:** Address legal, cultural, health, safety concerns in IoT solar micro-grid integration.	Societal	(√)
		Health	
		Safety	(√)
		Legal	
		Cultural	
PO7	**Environment and sustainability:** Explore sustainability and environmental benefits of IoT in solar micro-grids.	Societal	(√)
		Environmental	(√)
PO8	**Ethics:** Ensure ethical standards in integrating IoT system for solar-powered micro-grid.	Religious values	
		Professional ethics and responsibilities	(√)
		Norms	
PO9	**Individual work and teamwork:** Show leadership and teamwork in IoT solar micro-grid integration project	Diverse teams	(√)
		Multi-disciplinary settings	
PO10	**Communication:** Provide clear instructions, design documentation, and presentations for IoT integration.	Comprehend and write effective reports	(√)
		Design documentation	(√)
		Make effective presentations	(√)
		Give and receive clear instructions	(√)
PO11	**Project management and finance:** Manage engineering and financial aspects for successful IoT solar micro-grid integration.	Engineering management principles	(√)
		Economic decision-making	(√)
		Manage projects	
		Multidisciplinary environments	

5.4.3 Knowledge Profile

Table 14 Knowledge Profiles (K3 – K8) addressed in EEE 4700 for Project and Thesis.

K	**Knowledge Profile (Attribute)**	**Put Tick (√)**
K3	Develop a theory-based engineering course that integrates a smart IoT energy monitoring system into a solar-powered microgrid, ensuring students have a comprehensive understanding of the field.	(√)
K4	It will utilize advanced theoretical frameworks and engineering expertise for enhanced practice and innovation.	(√)
K5	Utilize engineering design skills to design an intelligent Internet of Things energy monitoring system for a solar-powered microgrid, ensuring efficient application of design concepts in real-world settings.	(√)
K6	Implement a smart IoT energy monitoring system for a solar-powered microgrid, utilizing your engineering knowledge and expertise in relevant technologies and procedures.	(√)
K7	Engineers play a social role, ensuring public safety and considering ethical issues. Integrating smart IoT energy monitoring into solar-powered microgrids is crucial for sustainable development.	(√)
K8	The integration of a smart IoT energy monitoring system for solar-powered microgrids requires informed decision-making and innovation, incorporating engineering research literature.	(√)

5.4.4 Complex Engineering Problem Solving

Table 15 Complex Engineering Problem Solving (P1 – P7) addressed

P	**Range of Complex Engineering Problem Solving**	**Put Tick (√)**
Attribute	Complex Engineering Problems have characteristic P1 and some or all of P2 to P7:	
Depth of knowledge required	**P1:** To integrate a smart IoT energy monitoring system for solar-powered microgrids, in-depth engineering knowledge at K3, K4, K5, K6, or K8 levels is needed for a foundation-based analytical approach.	(√)
Range of conflicting requirements	**P2:** Manage conflicting technical needs for effective engineering solutions	(√)
Depth of analysis required	**P3:** Use abstract thinking for modeling complex engineering problems.	(√)
Familiarity of issues	**P4:** Solve uncommon problems with specific expertise and creativity.	(√)
Extent of applicable codes	**P5:** Develop new standards and innovative solutions for unique issues.	(√)
Stakeholder involvement and conflicting requirements	**P6:** Address diverse stakeholder demands for a practical solution.	(√)
Interdependence	**P7:** Tackle intricate issues requiring a coordinated, comprehensive approach.	(√)

5.4.5 Complex Engineering Activities

Table 16 Complex Engineering Activities (A1 – A5) addressed

A	**Range of Complex Engineering Activities**	**Put Tick (√)**
Attribute	The integration of a smart IoT energy monitoring system for solar-powered microgrids necessitates interdisciplinary collaboration, advanced technology, risk management, stakeholder involvement, resource intensity, creativity, and regulatory compliance.	
Range of resources	**A1:** The organization utilizes a diverse range of resources, including staff, capital, tools, materials, information, and advanced technologies, to effectively tackle and resolve complex engineering issues.	**(√)**
Level of interaction	**A2:** Resolving large-scale challenges arising from diverse technical, engineering, and other concerns, requiring creative yet equitable solutions.	**(√)**
Innovation	**A3:** Utilizing engineering concepts and research knowledge to develop innovative solutions that enhance grid resilience and energy efficiency.	**(√)**
Consequences for society and the environment	**A4:** The impact of human activities on the environment and society can be significant, making it challenging to predict and mitigate their effects in various situations.	**(√)**
Familiarity	**A5:** Applying principles-based methodologies allows for creative and bold solutions to complex engineering challenges by going beyond previous experiences and pushing the boundaries of familiarity.	**(√)**

5.5 Socio-cultural, environmental[35], and ethical impact of the project

- Socio Cultural Impact: It raises awareness of energy issues, promoting responsible use and causing behavioral changes that will lead to a sustainable, environmentally conscious society.
- Environmental Impact: The project contributes to global energy conservation and sustainability, contributing to global efforts to reduce the carbon footprint.
- Ethical Impact: Promotes equitable energy access, fair billing, prevents overcharges, ensures transparency, and fosters community development.

CHAPTER 6

CONCLUSION & FUTURE WORKS

6.1 Conclusion

Integration of a Smart IoT Energy monitoring system for a solar-powered microgrid, as showcased in the case study of Sierra Leone's Kambia community, represents a significant step forward in sustainable energy management and rural electrification[35]. Throughout this project and thesis, we embarked on a journey to address the critical energy challenges faced by remote communities, leveraging innovative technologies and methodologies to foster energy access, reliability, and efficiency. The development and implementation of the Smart IoT meter signify a pivotal advancement in energy monitoring and management. By harnessing the power of Internet of Things (IoT) technology[36], we were able to gather real-time data on energy consumption, generation, and distribution within the microgrid network. This granular level of insight provided invaluable information for optimizing energy usage, identifying potential inefficiencies, and enhancing overall system performance. Moreover, the simulation of the microgrid using HOMER Pro software offered a robust platform for assessing the feasibility and effectiveness of the proposed energy infrastructure[37]. Through meticulous analysis and scenario testing, we were able to design a tailored solution that met the specific needs and constraints of the Kambia community. By modeling various configurations and scenarios, we could evaluate the economic, technical, and environmental implications of different energy strategies, ultimately guiding informed decision-making[38]. The case study of Sierra Leone's Kambia community served as a poignant reminder of the profound impact that access to reliable and sustainable energy can have on socio-economic development. In many rural areas across the globe, lack of electricity hinders progress in education, healthcare, agriculture, and entrepreneurship. By deploying smart IoT-enabled energy solutions, we can catalyze positive change, empowering communities to thrive and prosper. Furthermore, this project underscores the importance of collaboration and partnership in tackling complex challenges such as energy poverty[39]. Through close cooperation with local stakeholders, including government agencies, NGOs, and community leaders, we were able to co-create a solution that was both contextually relevant and culturally sensitive. By engaging with end-users throughout the design and implementation process, we ensured that the final solution aligned with their needs, preferences, and aspirations. Looking ahead, the integration of Smart IoT Energy monitoring systems holds immense promise for advancing the global transition to clean, renewable energy sources[40]. As we continue to refine and expand upon these technologies, we have the opportunity to drive greater efficiency, resilience, and sustainability across energy systems worldwide. Together, let us harness the power of innovation to build a brighter, more sustainable future for all.

6.2 Future Works

Addressing the challenges and improving the system for the integration of Smart IoT Energy monitoring in solar-powered microgrids requires a forward-thinking approach and a commitment to innovation. Here are detailed future works to tackle the identified challenges and enhance the system:

- Software Integration Challenges
- Limited Sensor Models
- Simulation of Real-Time Communication
- Scalability and Performance Issues

6.2.1 Future Directions:

a) **Advanced Data Analytics:**

- Leveraging advanced data analytics techniques, such as machine learning and artificial intelligence, will enable more sophisticated analysis of energy consumption patterns, predictive maintenance, and anomaly detection.
- Implementing real-time analytics algorithms can provide actionable insights for optimizing energy efficiency, identifying potential faults or failures, and improving overall system reliability.

b) **Integration with Renewable Energy Sources:**

- Expanding the integration of the monitoring system to include other renewable energy sources, such as wind or hydroelectric power, will enhance the resilience and sustainability of the microgrid.
- Developing algorithms for intelligent energy management and optimization across multiple renewable energy sources will maximize generation capacity and minimize reliance on non-renewable backup sources.

c) **Machine learning for predictive maintenance:**

- Implementing machine learning algorithms for predictive maintenance can help anticipate and prevent equipment failures before they occur, thereby minimizing downtime and reducing maintenance costs[41].
- By analyzing historical performance data and sensor readings, machine learning models can identify early warning signs of equipment degradation or malfunction, enabling timely intervention and maintenance.

d) **Blockchain Technology for Security:**

- Integrating blockchain technology into the energy monitoring system can enhance security and transparency by providing tamper-proof data storage and decentralized authentication mechanisms.
- Blockchain-based smart contracts can streamline energy transactions and enforce trustless agreements between stakeholders, ensuring fair and transparent energy exchange within the microgrid community.

By pursuing these future directions and addressing the identified challenges, the integration of Smart IoT Energy monitoring systems for solar-powered microgrids will continue to evolve as a cornerstone of sustainable energy management and rural electrification initiatives.

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