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Investigating the Potential of Building-Integrated Photovoltaics (BIPV) for Powering Public Buildings in Malawi: A Case of Bereu Health Centre in Chikwawa

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Research Paper

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ABSTRACT

The need for a sustainable energy transition towards clean, renewable sources has never been more urgent. This challenge is particularly acute in developing countries like Malawi, where a significant portion of the population lacks access to reliable electricity, hindering economic development and human well-being. In the rural areas in particular, a lot of public institutions including schools and hospitals have no access to electricity. This disrupts the effective operations of these entities. This study investigates the potential of Building-Integrated Photovoltaics (BIPV) to power public buildings in Malawi. Bereu Health Centre in Chikwawa District was selected as a case study. SketchUp modelling and EnergyPlus simulations were employed to assess the electricity generation potential and economic viability of BIPV systems for the health centre. Weather data from Ngabu weather station informed the simulations, ensuring realistic performance. The results indicate that the BIPV system is expected to generate 395.35 GJ/yr. of solar energy, exceeding the hospital's annual consumption of 55GJ/yr. This translates to a higher self-sufficiency and a reduction in grid reliance of more than 95% with an estimated annual cost savings on electricity bill of about MWK960,000.00.

These findings can inform policy decisions and promote the adoption of BIPV technology for sustainable energy solutions in the Malawi public sector.

1. Introduction:

A complex energy crisis grips the world, characterized by spiking fossil fuel prices. Geopolitical tensions and supply chain disruptions fuel this price surge, jeopardizing global economic stability and further accelerating climate change (International Energy Agency, 2022). This situation underscores the critical need for a swift transition to sustainable energy sources like renewables.

Malawi faces a complex energy crisis characterized by limited access, high costs, and dependence on unreliable grid electricity (McCauley et al., 2022). According to the World Bank, only about 23% of the Malawian population has access to electricity, with the vast majority residing in urban areas (The World Bank, 2023, 2024). Rural communities, which constitute a significant portion of the population, are particularly disadvantaged, often relying on traditional biomass fuels like firewood and charcoal for basic needs (The World Bank, 2023). This dependence on biomass contributes to deforestation, air pollution, and respiratory illnesses (World Health Organization, 2023).

Furthermore, Malawi's electricity grid suffers from chronic supply shortages, resulting in frequent and prolonged load shedding events (Chaima et al., 2023). These blackouts disrupt critical public services, impacting education, healthcare, and economic activity (Casey et al., 2020). A World Bank report highlighted the devastating effects of load shedding on education in Malawi, with schools experiencing power outages for up to 8 hours per day (The World Bank, 2010). These disruptions hinder learning, limit access to technology, and ultimately affect the quality of education for Malawian children. Similarly, healthcare facilities become compromised during blackouts, jeopardizing the delivery of essential medical services and patient care (UNICEF, 2018).

Building-Integrated Photovoltaics (BIPV) presents a promising solution to address energy challenges across the globe and equally in Malawi's energy sector. BIPV integrates solar photovoltaic (PV) panels directly into the building envelope, transforming rooftops, walls, or facades into electricity generators (Biyik et al., 2017). This technology offers several advantages over traditional rooftop solar installations. BIPV systems can provide aesthetic benefits by seamlessly integrating with the building design, while potentially reducing material and installation costs compared to separate mounting structures. Additionally, BIPV offers shade and thermal insulation, potentially lowering cooling energy demands (Aaditya & Mani, 2017).

The global BIPV market has witnessed significant growth in recent years, driven by technological advancements, cost reductions, and increasing awareness of its environmental benefits (Grand View Research, 2023). Several countries around the world have implemented successful BIPV projects, demonstrating the technology's potential for diversifying energy sources and enhancing building sustainability. Promoting BIPV adoption through government incentives and building regulations, may result in a thriving BIPV market and a growing number of successful BIPV installations (Mu'azu et al., 2021).

Malawi, with its abundant sunshine throughout most of the year, presents an ideal environment for solar PV technologies, including BIPV (Mohan & Ngwira, 2019). Figure 1 below from World Bank showcases the estimated photovoltaic power potential for Malawi. Chikwawa District, located in the southern region of Malawi, experiences particularly high solar radiation levels with an annual estimated potential of between 1500 to 1550 kWp (The World Bank, 2024), making it a prime location for exploring the potential of BIPV systems.

This research investigates the feasibility of BIPV technology in addressing the energy challenges faced by public buildings in Malawi, specifically focusing on Bereu Health Centre in Chikwawa District. By employing building modelling and energy simulations, this study aims to assess the electricity generation potential and economic viability of BIPV systems for the health centre.

The electricity demand has been growing consistently by at least 6-8% per annum in Malawi (Taulo et al., 2015), hence the findings of this research can provide valuable insights into the potential of BIPV technology for powering public buildings in Malawi, particularly in rural areas with limited grid access. If successful, this research could pave the way for wider adoption of BIPV systems across the country, subsequently contributing to meeting that demand. By harnessing the power of the sun, BIPV can contribute to energy security, improve the reliability of public services like education and healthcare, and ultimately promote sustainable development in Malawi (Pillai et al., 2022).

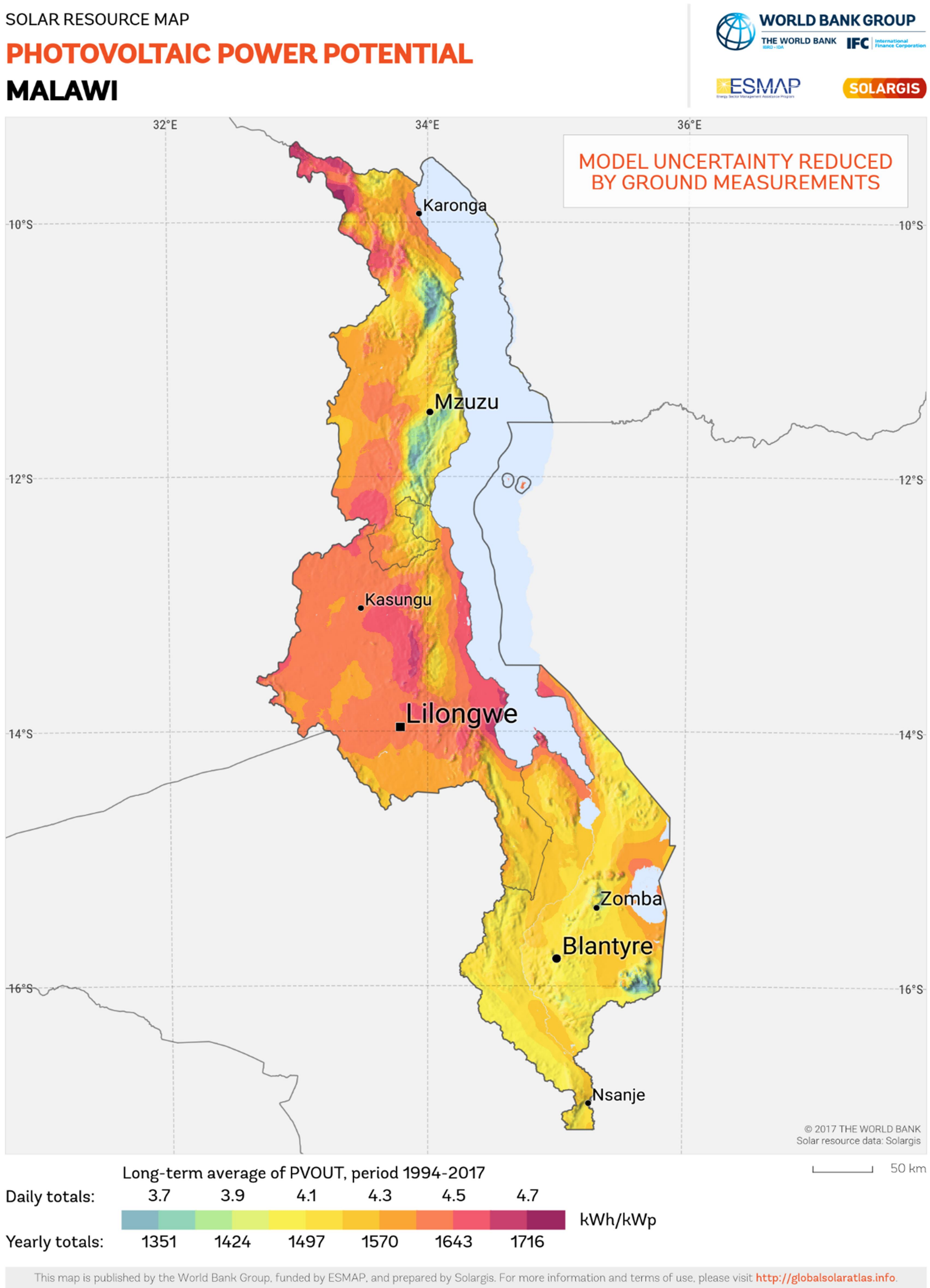


***Figure 1**: Photovoltaic power potential in Malawi (https://solargis.com/maps-and-gis-data/download/malawi)*

2. Methodology

2.1. Building Selection

The chosen building for this BIPV system modelling is Bereu Health Centre located in Chikwawa district, Malawi. The public infrastructure which covers 319.55m^2 was chosen for a number of reasons. Firstly, Chikwawa district boasts an estimated annual photovoltaic potential of about 1500 kWp/m^2 according to World Bank Solar resource data solargis (Solargis, 2017), this high solar radiation makes it an ideal location for a BIPV system, maximizing potential electricity generation.

Secondly, Bereu Health Centre already utilizes a small solar photovoltaic (PV) system with 14 units of 300W solar panels to meet some of its electricity demand. This existing system demonstrates the facility's commitment to renewable energy and provides valuable data for the BIPV model starting point. Analysing the performance of the current system informs the design and size of the proposed BIPV installation.

Hospitals and health centres are crucial public buildings with a constant demand for electricity to operate essential medical equipment. Reliable power is vital for patient care, vaccinations, and maintaining life-saving medical equipment. By focusing on a health centre, this research directly contributes to improving healthcare delivery and patient well-being in Malawi.

Lastly, data availability also played a role in selecting Bereu Health Centre**.** A health centre under government management offered easier access to this data compared to private buildings. Figure 2 below shows Bereu Health Centre.

Figure 2:*Bereu Health Centre (Front View)*

2.2. Data Collection

Data collection is a crucial part of every research. In particular, building modelling requires as accurate data as possible to create a digital twin that accurately mimics the real building. Herein, a period of 3 weeks was dedicated for data collection physically at the premises and interacting with technicians. The data collected included building dimensions, building materials, electrical equipment, ratings and operational schedules, energy consumption, energy annual bills, and solar performance among others. Table 1 below summarizes the building parameters utilized in the subsequent SketchUp modelling stage.

Feature	Value
Length	32 meters
Width	10 meters
Height	5 meters
Wall Material	Masonry (Bricks + Cement + Sand)
Roof Material	RB Iron Sheets (Gauge 28), Galvanized IBR Sheets
Ventilation	2 Concrete Louvered Windows (2.20m x 1.70m)
	15 Wooden Louvered Windows (glass inserts) (0.50m x 0.85m)
	5 Wooden Louvered Windows (smaller, glass inserts) (0.40m x 0.65m)
	5 Casement Windows (steel frames, glass inserts) (1.50m x 1.20m)

Table 1: A summary of the building parameters

2.3. SketchUp Modelling and OpenStudio Signing

A precise 3D model of the health centre was constructed using SketchUp Pro 2023 as seen in figure 3 below. The model is a digital twin of the actual building's geometry, including its dimensions, wall material , roof type, windows, doors, and other significant architectural features. Particular emphasis was placed on accurately modelling the roof area, as it is crucial for determining BIPV system placement and potential solar energy generation.

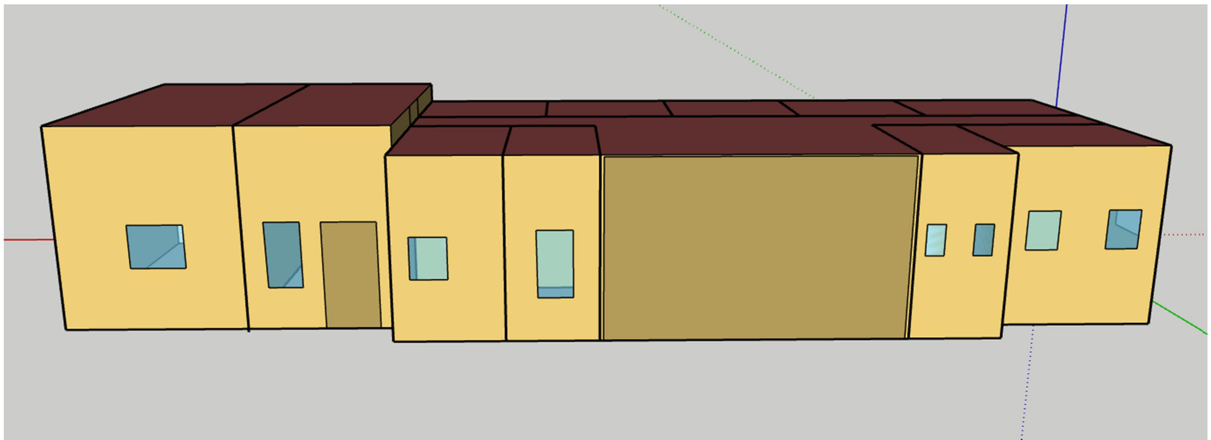


***Figure 3**: SketchUp model of Bereu Health Centre*

Upon completion of the detailed SketchUp model, it was exported as an OpenStudio Model (osm) file compatible with OpenStudio software version 3.6.1. This export process ensures seamless integration of the building geometry into the energy simulation environment (Lee et al., 2021). In OpenStudio, various objects were assigned to accurately represent the building's thermal properties, energy consumption patterns, and potential for BIPV integration. This critical step involved defining:

Spaces: Individual spaces within the health centre including 2 waiting areas, consultation rooms, laboratory, and the pharmacy, were defined.

Surfaces: Building surface walls, roof, floor were assigned with appropriate material properties, thermal conductivity, thickness among others based on the collected data.

Schedules: Operational patterns for lighting, people, equipment, and HVAC systems were modelled using schedules informed by the collected data.

Thermal Loads: Internal heat gains within the building spaces were defined based on equipment power ratings and occupancy levels.

HVAC System: The buildings 2 York brand air conditioners and 3 fans were modelled in OpenStudio.

Power Ratings: Power ratings are assigned to various equipment within the building based on the collected data.

Figure 4 indicates the schedules signed in OpenStudio for different equipment including lighting, HVAC system, people, and equipment.

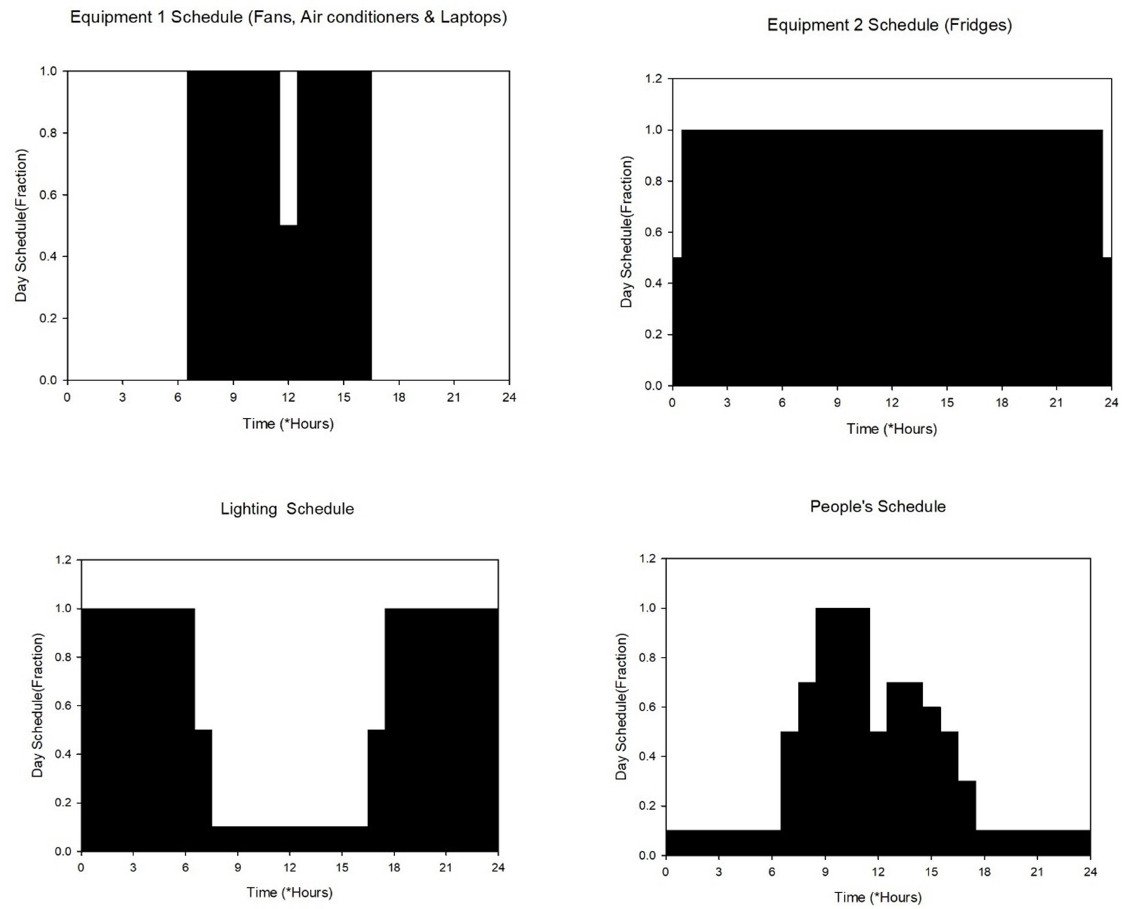


Figure 4: *Schedules assigned in OpenStudio for (a)Equipment 1, (b) Equipment 2, (c)Lighting, and (d)People.*

2.4. Model Validation

Model validation was necessary before proceeding with BIPV system simulation, it was crucial to validate the accuracy of the OpenStudio model created in the previous stage. This validation process ensured the model realistically reflects the actual energy performance and indoor weather condition of Bereu Health Centre.

Mean Absolute Percentage Error (MAPE) was utilized for model validation. MAPE is a statistical method commonly used to quantify the accuracy of a model's predictions compared to actual measured data (Kim & Kim, 2016). It expresses the average difference between simulated and measured values as a percentage. Eq.(1) below shows the MAPE formula for calculating percentage error where y_s is simulated data and y_m *is* measured data, n is the number of data sets.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}(|\frac{y_s - y_m}{y_m}|) * 100 \qquad (1)$$

For this research, a MAPE of less than 10% was considered an acceptable threshold for model validation. This signifies that on average, the simulated values, where in this case we focused on indoor temperature and energy consumption, deviate by no more than 10% from the actual measured data points.

If significant discrepancies were identified between the simulated and measured data points, resulting in a MAPE exceeding 10%, the OpenStudio model underwent iterative refinement (An et al., 2024). This involved adjusting material properties, occupancy schedules, equipment power ratings, or other relevant parameters within the model. The validation process continued until a satisfactory level of agreement was achieved between the model's predictions and the actual data, reflected by a MAPE below the 10% threshold.

2.5. BIPV Modified Simulation and Assessment

Following a successful model validation, the research progressed to simulating the integration of a BIPV system into the health centre’s existing energy infrastructure.

2.5.1. BIPV System Design:

A BIPV system was designed specifically for Bereu Health Centre by modifying the initial model. The modified integrated BIPV system had a cell efficiency of 0.18, inverter efficiency of 98%, and 0.78 fraction of each roof surface that has PV. The modified system is shown in figure 4 below.

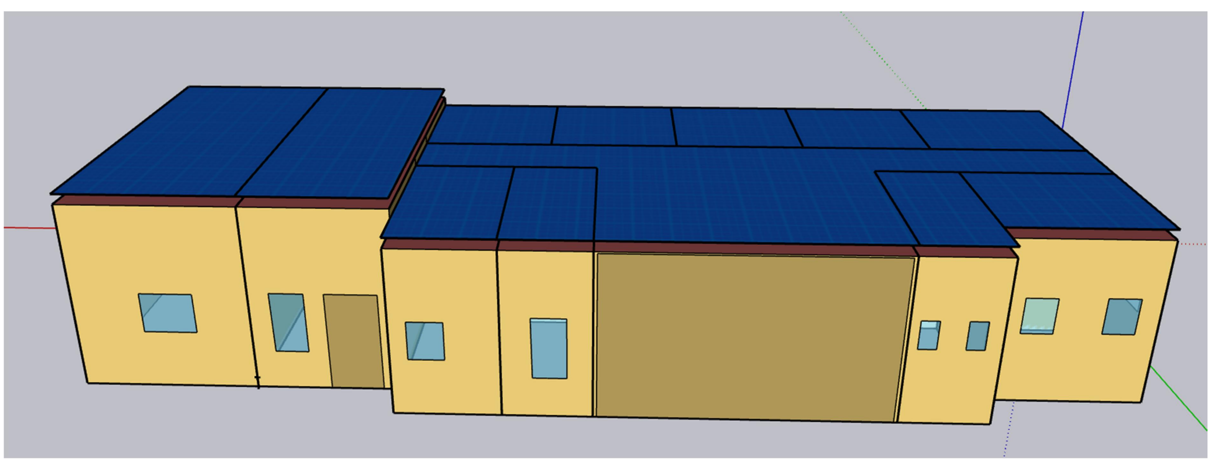


***Figure 5**: Bereu Health Centre PV Integrated Building*

The integrated design among others considered roof area and orientation. The available area and orientation towards the sun were crucial factors in determining the size and layout of the BIPV system. The system also took into consideration solar irradiation data**.** Solar radiation data for Chikwawa district, obtained Ngabu weather station EnergyPlus Weather File (epw) informed the potential electricity generation capacity of the BIPV system.

The energy consumption profile of the validated OpenStudio model, accurately reflecting the health centre's energy demand, was used to optimize the BIPV system size to meet a significant portion of the facility's electricity needs.

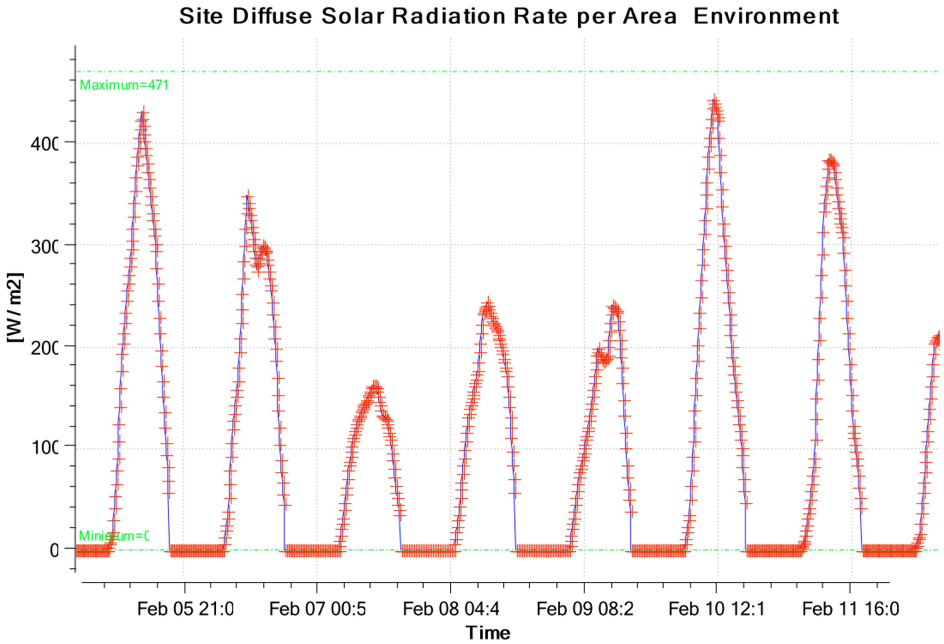
The modified model was run to assess the impact of the BIPV system on the health centre's energy performance. Key metrics that were analysed include:

- **Electricity Generation:** The annual electricity generation potential of the BIPV system were estimated.
- **Energy Consumption Reduction:** The simulated reduction in electricity consumption from the national grid due to BIPV integration were evaluated.
- **Cost Savings:** Based on the estimated reduction in grid reliance, potential cost savings on the health centre's electricity bills were calculated.
- **Grid reliance reduction percentage:** The reduction percentage in relying on the nation's electricity grid.
-

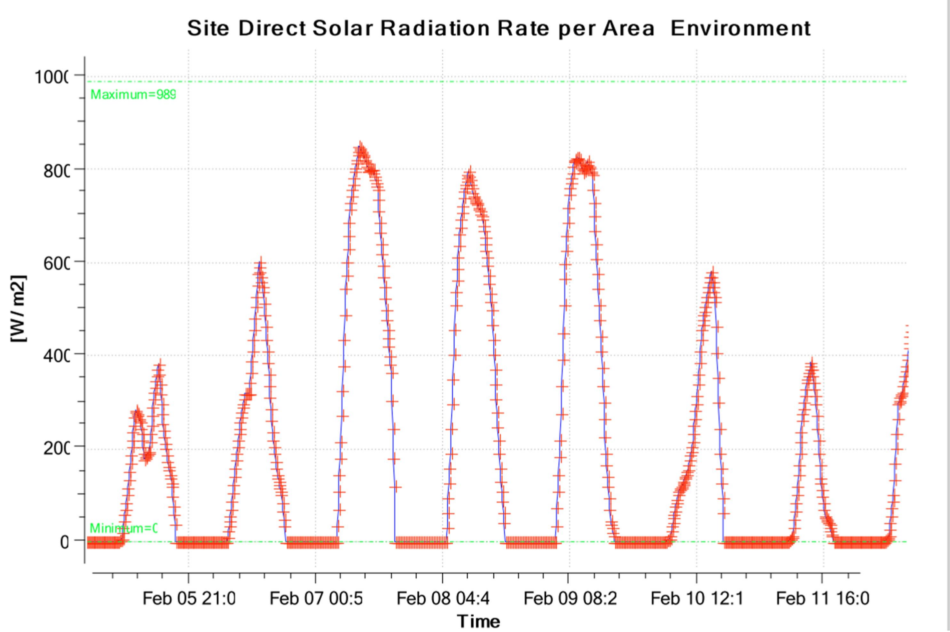
3. Results and Discussion

3.1. Model Validation

The model validation process was conducted to ensure the accuracy of the model for subsequent stages. The model validation parameters were indoor temperature and energy consumption. The PV energy generation relied more on the site solar direct and diffuse radiation per area as plotted in the graphs in figure 6 below.



(a)



(b)

***Figure 6**: (a) Site diffuse solar radiation (b)Site direct solar radiation.*

3.1.1. Annual Energy Consumption

This represents the total energy usage of the hospital over a year. Bereu Health Centre recorded monthly electricity bills were used to determine the actual annual energy consumption.

$$Annual\ Energy\ Consumption\ (kWh) = \frac{Monthly\ Bill\ (MWK)}{Cost\ per\ kWh\left(\frac{MWK}{kWh}\right)} * 12 \qquad (2)$$

The calculation utilises the cost of electricity in Malawi at the time of publication which stands at MWK 173.70/ kWh according to Malawi Energy Regulatory Authority (MERA, 2024). The results show that Bereu consumes about 5,526.77 kWh annually.

3.1.2. Temperature

Indoor temperature is another crucial factor influencing energy consumption for heating and cooling systems. The temperature data for validation was obtained by averaging readings from Consultation Room 1, Consultation Room 2, and the Patients Main Waiting Area. The figure below shows day average simulated temperature in the consultation room 1 and 2.

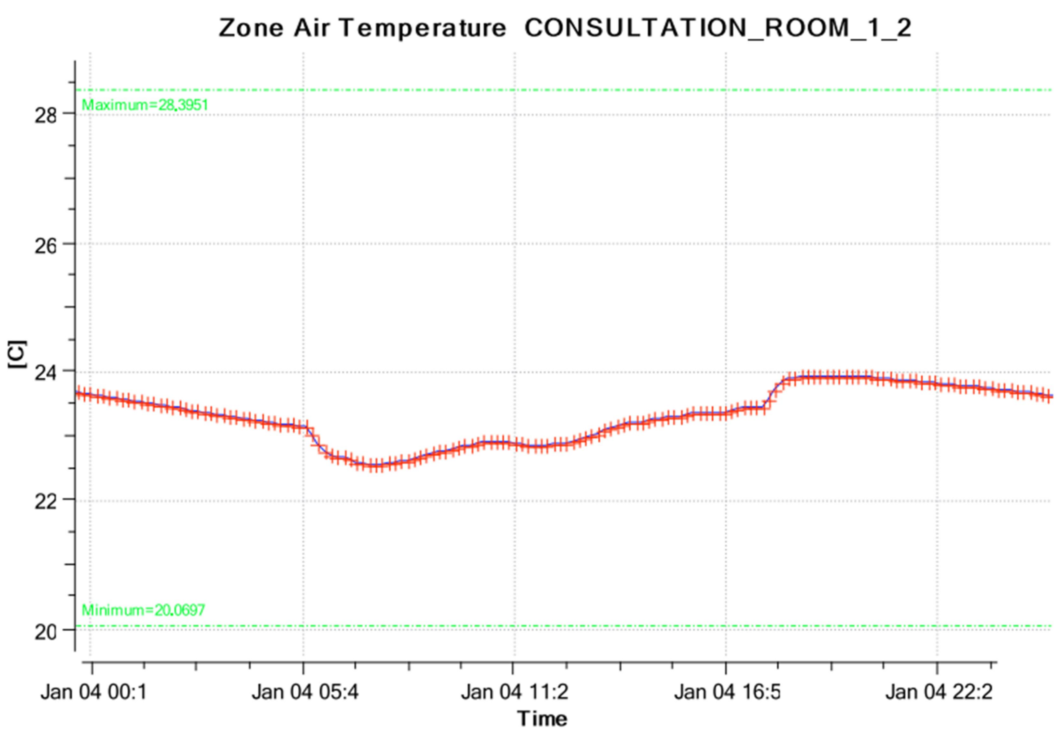


Figure 7: Consultation Rooms 1 and 2 Average Simulated Indoor Temperature

MAPE Performance

The analysis yielded the Energy Consumption MAPE value of 8.3% error and Temperature value of 2.9% error. The obtained MAPE values fall below the commonly recommended tolerance level of 10% for building energy simulation models. This indicates a good agreement between the predicted values from the model and the actual collected data. Therefore, the model was considered valid and suitable for subsequent BIPV design.

3.2. Techno-Economic Analysis:

The implementation of the Building Integrated Photovoltaic (BIPV) system is projected to generate 295.35 GJ/yr of solar energy based on the simulated BIPV model in EnergyPlus. This significantly exceeds the Bereu Health Centre's current annual electricity consumption of 55.18 GJ/yr. The following parameters were calculated to ascertain the economic benefits of the system and analyse the energy performance of the modified model.

3.2.1. **Self-Sufficiency Rate**

The self-sufficiency rate (SSR) indicates the percentage of the hospital's electricity needs that can be met by the BIPV system (Hassan et al., 2023). We can calculate this using the following formula.

$$SSR = \frac{BIPV\ Annual\ Gen\ (\frac{Gj}{yr})}{Health\ Centre\ Annual\ Cons(\frac{Gj}{yr})} * 100 \qquad (3)$$

The BIPV system is expected to generate more than enough energy to cover the hospital's entire electricity demand, achieving an exceptional self-sufficiency rate of over 535%.

3.2.2. **Reduction in Grid Reliance**

The reduction in grid reliance (RGR) represents the percentage decrease in dependence on the national grid for electricity (Al-Shetwi et al., 2020). We calculate this using Eq.(5)

$$RGR = \left(1 - \frac{Consumption\ after\ BIPV\left(\frac{Gj}{yr}\right)}{Consumption\ before\ BIPV\left(\frac{Gj}{yr}\right)}\right) * 100 \qquad (4)$$

Since the BIPV system is expected to generate more than the hospital's consumption, we can estimate that the hospital will rely minimally or completely off grid after implementation. The estimated RGR is calculated to be 100%.

3.2.3. **Potential Electricity Cost Savings**

The hospital currently relies on ESCOM for approximately 41% of its electricity needs. The following calculation analyses the cost saved with the modified model.

Cost Savings Calculation:

To estimate the potential electricity cost savings from reduced reliance on ESCOM, we use Eq.(7) utilizing ESCOM Rate of 1 kWh = MWK 173.70 and a conversion factor of Energy Conversion 1 GJ = 277.78 kWh .

$$Cost\ Savings\ (MWK) =$$

$$Escom\ monthly\ reliance\left(\frac{\text{kWh}}{\text{month}}\right) * 12(month) * 1kWh\ Rate\ (MWK/kWh) \tag{5}$$

The BIPV system has the potential to generate significant cost savings on the electricity bill, with an estimated reduction of about MWK960,000.00 annually.

The results indicate that the BIPV system has the potential to be a highly beneficial solution for Bereu Health Centre, delivering significant economic and environmental advantages. By generating clean solar energy, the BIPV system can help mitigate climate change and promote a more sustainable future for Malawi (Bass et al., 2020).

3.3. **Social Impact**

The BIPV project offers several potential social benefits including increased energy security for the hospital which ensures uninterrupted healthcare services, even during grid outages. Furthermore, the BIPV sector has the potential to create new job opportunities, fostering economic development within

Malawi. Additionally, with excess energy generation, the BIPV system could be explored as a potential source of power for nearby communities, expanding its positive social impact.

3.4. **Alignment with National Policies**

The success of this Bereu Health Centre's BIPV system research aligns with Malawi's Vision 2063 "***Kusintha Dziko Lathu Mokomera Aliyense***" pillar number 2 on hydro-electricity dependence reduction and enhancing alternative energy sources (Malawi Vision 2063, 2020). The project also contributes to achieving the United Nations Sustainable Development Goals (SDGs) by focusing on affordable and clean energy (SDG 7) and taking action to combat climate change (SDG 13) (Sorooshian, 2024). Furthermore, it supports Malawi's commitments under Paris Agreement on climate change. By implementing this BIPV system, Bereu Health Centre can serve as a model for sustainable energy solutions in Malawi's public infrastructure.

4. Conclusion

This study has utilized EnergyPlus building energy simulation software to evaluate the potential of a Building Integrated Photovoltaic (BIPV) system for Bereu Health Centre in Chikwawa district in Malawi. The results demonstrate a compelling case for BIPV technology. The BIPV system is projected to generate significantly more energy of about 295.35Gj/yr than the hospital's current demand of about 55Gj/yr, achieving an exceptional self-sufficiency rate and a substantial reduction in reliance on the national grid. This translates to potential annual cost savings of about MWK 960,000.00 on electricity bills.

These findings highlight the power of EnergyPlus simulations in informing energy-efficient design strategies for public buildings in Malawi. The success of the BIPV system at Bereu Health Centre aligns with national goals for sustainable development and clean energy adoption, paving the way for wider implementation of BIPV technology across the Malawian public sector.

5. Credit authorship contribution statement

Alfred Kampira Levison: Data collection**,** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Professor N. Nasruddin**: Conceptualization, Supervision, Formal analysis, Investigation, Methodology, Resources, **Wongani Ziba:** Data collection**,** Resources, Review-Original draft.

6. Declaration of Competing Interest

The authors herein declare that they have no known competing financial interests, personal relationships, or reasons whatsoever that could have influenced the work reported in this paper.

7. Data availability

The authors do not have permission to share data.

8. Acknowledgment

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