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Design And Analysis of a Solar-Powered E-Bike Charging System to Advance Innovation in Green Technologies

A. Musa[1]*, K. F. Adebara[2], H. A. Mojeed[3], K. Abdulfattah[4]

[1,2,3,4]Department of Electrical and Computer Engineering, Kwara State University, Malete, Nigeria.
[1]Centre for Artificial Intelligence and Machine Learning Systems, Kwara State University, Malete, Nigeria.

[1]abdulwaheed.musa@kwasu.edu.ng, [2]adebarakhalid@gmail.com, [3]mojeedhassan304@gmail.com, [4]sisimikdj@gmail.com
*Corresponding Author: abdulwaheed.musa@kwasu.edu.ng

ABSTRACT

In the face of climate change and the urgent need for sustainable practices, higher education institutions play a critical role in driving innovation in green technologies. This paper presents an approach to the design of a solar-powered e-bike charging system tailored for university campuses. With rising concerns about environmental sustainability, the work focuses on reducing carbon emissions and promoting clean mobility solutions on university campuses. The design accommodates specifications for a 6 km radius surrounding the school, a two-day lifespan, and 100 electric bicycles. The experiment's findings indicate that the solar-powered e-bike design requires 99 solar panels with a capacity of 150 Wp, 9 SSCs with a capacity of 100 A, and three inverters with a capacity of 2,500 W. Simulations were carried out to assess energy efficiency, system capacity, and potential environmental impact. The results indicate that the proposed system can provide consistent, renewable energy for e-bike charging, significantly lowering the carbon footprint of campus commuting. Additionally, the design offers scalability and adaptability to other institutional settings, presenting opportunities for broader adoption. This paper highlights the potential of student-led innovation in driving sustainable infrastructure within higher education. It is projected that this device will reduce exhaust emissions by 7.62 tons of CO_2 per year once it is entirely operated.

Keywords: Green technology, Renewable energy, Sustainability, E-bike charging

1. INTRODUCTION

1.1 Background and Motivation

The rapid industrialization and urbanization of modern societies have led to increased reliance on fossil fuels, resulting in significant environmental challenges such as air pollution and climate change (Intergovernmental Panel on Climate Change [IPCC], 2021). In response, the world is progressively shifting toward green and sustainable technologies (United Nations, 2020). One such innovation is the use of electric bicycles (e-bikes), which offer an eco-friendly alternative to traditional petrol-powered transportation (Cherry & Cervero, 2007), and also, due to their relatively low cost, minimal energy consumption, and suitability for short-distance travel. However, the environmental advantage of e-bikes is closely tied to the source of their charging energy; when charging relies on grid electricity generated from fossil fuels, the sustainability benefits are diminished.

Solar photovoltaic (PV) energy presents a compelling alternative, especially in regions with high solar potential. Standalone solar charging infrastructure can deliver renewable energy for e-bikes without burdening the grid, making off-grid systems particularly attractive in areas with limited or unreliable electricity access. In practice, however, designing reliable and scalable solar-powered charging stations involves addressing several technical challenges, such as matching generation with variable irradiance, sizing energy storage for multi-day autonomy, and ensuring robust performance under real-world load conditions.

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Kwara State, Nigeria.

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Several recent studies have contributed to understanding these challenges. Mishra et al. (2022) developed a standalone PV system for e-bike charging that maintained stable DC bus voltage under variations in solar irradiance, demonstrating the technical feasibility of off-grid PV solutions for workplace charging applications. Similarly, Afzal et al. (2023) investigated a hybrid wind/PV charging station for e-bikes using MATLAB/Simulink modelling, providing insights into how complementary renewable resources and storage can support continuous operation and cost evaluation in onshore and offshore contexts. Other research has examined broader PV-based charging infrastructure for micro mobility, highlighting trends and architectural factors that influence the design of sustainable charging networks.

Despite these advances, notable gaps remain. Many existing studies address small-scale or prototype systems that do not explicitly consider large-scale deployment or multi-day energy autonomy. Others focus on hybrid configurations involving multiple renewable sources without isolating the impacts of solar PV sizing and storage for off-grid operation. Furthermore, studies often rely on a single simulation tool or analytical model, limiting cross-validation of dynamic behavior and long-term performance. Finally, few works quantify environmental outcomes such as carbon dioxide emission reduction in a manner that directly supports sustainability planning for institutional adoption.

This study addresses these gaps by presenting the design and simulation-based evaluation of a fully off-grid solar-powered e-bike charging system intended for campus-scale deployment. The proposed system is designed to support 100 electric bicycles with a two-day energy autonomy requirement, ensuring reliability under typical variability in solar irradiance. We adopt a transparent, reproducible sizing methodology that integrates load estimation, PV generation, battery storage, and power conversion within a unified analytical framework. System performance is validated using MATLAB/Simulink to capture dynamic energy flow and battery state-of-charge behavior, and HOMER Pro to verify annual energy balance and system viability.

The remaining sections of this paper are structured as follows: Section 2 presents the methodology. Section 3 focuses on the Discussion of results, and finally, Section 4 concludes the paper.

1.2 Literature Review

The transition toward sustainable energy in transportation has become imperative in mitigating the effects of climate change and promoting environmental stewardship. One of the promising innovations is the use of solar-powered charging systems for electric bikes (e-bikes), especially within institutional settings such as universities, where mobility, environmental consciousness, and educational innovation intersect. This literature review synthesizes scholarly efforts in the design, simulation, and implementation of solar-powered charging systems for e-mobility, particularly as they relate to higher education settings and the development of green technologies.

Ranasinghe et al. (2024) developed a solar-powered electric bicycle that integrates photovoltaic charging with a lightweight electric drive system. Their work emphasizes practical prototyping and evaluates the bike's performance under real operating conditions. The study highlights the efficiency and cost-effectiveness of using solar energy for small-scale mobility, demonstrating that the system can reduce dependence on grid electricity. However, its testing was limited to a specific environment, which restricts broader applicability. Despite this, the project provides useful insights into designing renewable-energy transportation systems and supports ongoing innovations in sustainable mobility.

This study by Mishra et al. (2022) developed a simulation-based model for a standalone solar-powered electric bike system. Their study focused on optimizing energy efficiency and assessing system performance through computational analysis. This work is valuable for understanding the technical feasibility of solar-powered e-bikes, providing foundational insights into system design and potential operational benefits. However, the lack of experimental validation limits its practical applicability, highlighting the need for real-world implementation to fully assess performance in varied environmental conditions.

Similarly, Suripto et al. (2022) investigated the design and performance of a solar-powered e-bike charging station for university campuses. Their analysis emphasized optimizing energy usage, station capacity, and environmental benefits. The study provides detailed insights into system design considerations, including solar panel sizing, battery storage, and charging efficiency. While primarily theoretical, the work offers a clear framework for implementing solar-based e-bike infrastructure, demonstrating its potential to support sustainable campus mobility and reduce reliance on conventional energy sources.

In another approach, Tharwin Kumar and Rajan (2023) proposed a hybrid photovoltaic–wind system for electric vehicle charging, aiming to enhance energy reliability and sustainability. The study focused on integrating solar and wind sources to maintain a consistent power supply under fluctuating environmental conditions. While the system was not specifically designed for e-bikes, it provides valuable insights into renewable energy management, storage requirements, and hybrid system optimization. The work highlights the potential of combining multiple renewable sources to support sustainable mobility solutions, though practical deployment may involve higher costs and technical complexity.

Collectively, these studies reveal a progressive trend toward integrating renewable energy with e-mobility and underscore the potential of higher education institutions to serve as living labs for sustainable innovation. They reflect a spectrum of development from theoretical simulations to real-world prototypes, highlighting critical factors such as cost, scalability, environmental impact, and user accessibility. This body of literature provides a firm theoretical and practical foundation for designing a solar-powered e-bike charging system tailored to a higher education setting. It also supports the assertion that universities are well-positioned to lead in deploying green technologies that benefit both their academic communities and broader urban ecosystems.

A recent study by Dukpa et al. (2023) conducted a comparative analysis of on-grid and off-grid solar photovoltaic (PV)-based electric-vehicle charging stations using a mixed-integer linear programming (MILP) framework for optimal operation and profit maximization. Their model integrates a solar PV array with a battery energy storage system (BESS), forecasts of solar generation, and probabilistic arrival patterns of vehicles to dynamically schedule charging, grid import/export, and battery usage. The study shows that a grid-connected configuration, allowing import during energy deficits and export during surplus, yields better profitability and operational flexibility than a purely off-grid system, which otherwise would require a very large battery capacity to meet demand reliably. The findings highlight how storage, smart scheduling, and grid interaction can mitigate the intermittency of solar power, making solar-PV charging stations more economically and technically viable for sustainable mobility infrastructure. Although the focus of their work was primarily on electric cars rather than e-bikes, their findings reinforce the overall advantages of transitioning to solar energy for transportation applications. The economic efficiency and reduced reliance on fossil fuels presented in their work further justify the adoption of solar-powered systems in institutional environments such as universities. However, the study's limited attention to lightweight vehicles like e-bikes means that specific technical configurations and usage patterns relevant to the current study were not directly addressed.

Also, Falk et al. (2020) explored the use of second-life lithium-ion batteries in off-grid solar-powered systems, focusing on socio-economic benefits for rural communities. Their study analyzed technical performance, cost-effectiveness, and potential environmental advantages of repurposing used EV batteries for energy storage. While the work targeted rural electrification rather than e-bike charging, it provides valuable insights into sustainable energy management, battery lifecycle extension, and cost reduction strategies. The findings demonstrate how second-life batteries can enhance the feasibility and resilience of off-grid renewable energy systems.

Mphephu et al. (2025) designed and implemented a hybrid solar–grid-powered charging system for electric bicycles. Their study combined solar energy with grid support to ensure reliable and continuous charging, optimizing both energy efficiency and system availability. The research included practical implementation, performance testing, and analysis of operational reliability, highlighting the benefits of integrating renewable energy with conventional sources. This work provides a useful framework for developing sustainable and resilient e-bike charging infrastructure, particularly in environments with variable solar conditions.

Mouli et al. (2020) proposed a sustainable e-bike charging station capable of AC, DC, and wireless charging powered entirely by solar energy. Their study focused on integrating multiple charging modes with renewable energy to maximize flexibility and user convenience. Performance analysis highlighted system efficiency, energy management, and the feasibility of fully solar-powered operations. Although primarily a conceptual and experimental study, it demonstrates the potential of multifunctional, solar-based charging stations to support sustainable urban mobility and reduce reliance on conventional electricity sources.

Kuyinu et al. (2025) designed and constructed a long-lasting solar charging system for e-scooters, focusing on durability, energy efficiency, and practical usability. Their study included prototyping and performance evaluation under real-world conditions, highlighting reliability and sustained operation. The work demonstrates how solar-based charging solutions can extend vehicle runtime while promoting sustainable mobility. Although specific to e-scooters, the design principles and insights can be adapted to other light electric vehicles, including e-bikes, for campus or urban applications.

Three notable research comparison is presented in table 1 to show the state of the researches in this area. Mishra et al. (2022) presented a standalone solar-powered e-bike charging model with a focus on analytical load modelling; however, the study was limited to small-scale deployment and did not consider multi-day energy autonomy or system robustness under variable irradiance. Mouli et al. (2020) developed a versatile solar-powered charging station supporting AC, DC, and wireless charging, but the emphasis was placed on charging flexibility rather than storage autonomy or campus-scale capacity planning. Dukpa et al. (2023) conducted a comprehensive comparative analysis of on-grid and off-grid solar photovoltaic-based electric vehicle charging stations; nevertheless, the system design was oriented toward electric vehicles and incorporated grid interaction, which reduces its applicability to fully off-grid e-bike charging scenarios.

In contrast, the present work focuses explicitly on a fully off-grid, campus-scale solar-powered e-bike charging system designed to support 100 electric bicycles with two-day energy autonomy. By combining transparent component sizing with dual-tool simulation validation and quantified environmental impact assessment, this study extends existing research toward practical, large-scale deployment in energy-constrained environments.

Table 1: The comparison of three notable research of e-bike

Parameter	Mishra et al. (2022)	Mouli et al. (2020)	Dukpa et al. (2023)
System type	Solar-powered e-bike charging	Solar-powered e-bike charging	Solar PV-based EV charging
Deployment scale	Small-scale (single/few bikes)	Pilot-scale station	EV charging station
Grid dependency	Fully off-grid	Off-grid	On-grid & off-grid
Energy autonomy	Not explicitly defined	Limited (no multi-day autonomy)	Not emphasized
Battery technology	Conventional battery storage	Li-ion with multiple charging modes	Grid–PV integrated storage
Charging modes	DC charging	AC, DC, and wireless charging	AC charging
Validation approach	Analytical modelling	Experimental prototype + simulation	Simulation-based analysis
Environmental impact analysis	Not quantified	Qualitative	Not quantified

1.3 Contribution

This study adds to ongoing efforts in sustainable campus transportation by developing an off-grid, solar-powered e-bike charging system that is intended for practical deployment within a university setting in a developing-country. Rather than remaining at a conceptual level or concentrating on small experimental setups, the work places emphasis on system-level design, realistic capacity planning and operational practicality under actual campus conditions.

The main contributions of this work can be summarized as follows. First, a campus scale solar charging infrastructure capable of serving up to 100 electric bicycles with two days energy usage is designed and analytically evaluated using solar irradiance conditions representative of Nigeria. Second, the study presents a clear reproducible sizing approach that systematically connects energy demand estimation with photovoltaic generation, battery storage requirements, and power conversion capacity within a unified framework. Third, the proposed system is validated through simulation using MATLAB/Simulink and HOMER Pro to examine energy balance, battery state-of-charge behavior, and overall system reliability under varying load and solar conditions. Finally, the environmental benefit of the system is quantified by estimating its annual cardon dioxide (CO_2) emission reduction, thereby directly linking engineering performance to sustainability objectives relevant to higher education institutions.

2. MATERIALS AND METHODS

This section presents the analytical and simulation-based methodology adopted in the design of the solar-powered e-bike charging system, including load estimation, photovoltaic (PV) sizing, battery storage design, and system validation. The proposed system was modeled as an integrated renewable energy setup comprising photovoltaic generation, storage, and power conversion units. The overall design configuration of the system is illustrated in Figure 1. The figure shows the flow of energy from the solar PV array through the charge controller and battery bank to the inverter and charging outlets.

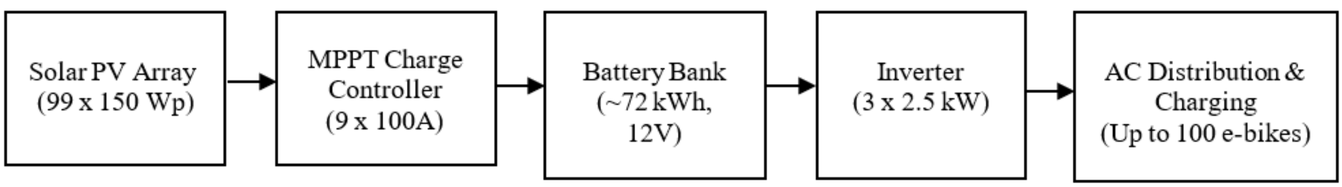

Figure 1: Block Diagram of the Solar-Powered E-Bike Charging

2.1 Load Estimation

Each electric bicycle is assumed to operate with a battery rated at 36 V and 10 Ah, corresponding to an energy capacity given in Equation (1)

$$E_{bike} = V \times Ah = 36 \times 10 = 360\ Wh = 0.36\ kWh \quad (1)$$

For a fleet of N=100 e-bikes, the total daily energy demand is estimated using Equation (2)

$$E_{daily} = N \times E_{bike} = 100 \times 0.36 = 36\ kWh/day \quad (2)$$

To ensure uninterrupted operation during periods of low solar availability, a two-day usage is considered, resulting into a required storage capacity as expressed in Equation (3)

$$E_{storage} = 2 \times E_{daily} = 72\ kWh \quad (3)$$

2.2 Photovoltaic System Sizing

The daily energy output of a single PV panel is estimated by Equation (4)

$$E_{PV} = P_{rated} \times H_{sum} \quad (4)$$

P_{rated} = 150 Wp is the panel rating and H_{sum} = 5.5 kWh/m^2/day is the average peak sun hours in Nigeria.

The minimum number of panels required to meet daily demand is given in Equation (5)

$$N_{PV,min} = \frac{E_{daily}}{E_{PV}} \approx 44 \quad (5)$$

To account for system losses, battery charging inefficiencies, and storage autonomy, the number of panels is increased to 99 units, providing sufficient generation margin and operational robustness.

2.3 Battery Storage Design

The required battery capacity is determined from the storage energy requirement as estimated using Equation (6)

$$C_{bat} = \frac{E_{storage}}{\eta_{bat}} \quad (6)$$

η_{bat} represents battery efficiency. Deep-cycle batteries are selected to ensure long life and stable operation under repeated charge–discharge cycles.

2.4 Power Conversion and Control

Maximum Power Point Tracking (MPPT) charge controllers are employed to maximize energy harvest from the PV array. Inverter capacity is selected to satisfy peak simultaneous charging demand, ensuring safe and reliable AC power delivery to the charging points.

2.5 Simulation and Validation

The system is modeled in MATLAB/Simulink to evaluate dynamic power flow, battery state-of-charge (SOC), and system response under varying irradiance conditions. HOMER Pro is used to verify system sizing, assess annual energy yield, and validate the off-grid feasibility of the configuration. Key performance indicators include energy balance, SOC stability over a 48-hour cycle, and system reliability.

3. RESULTS AND DISCUSSION

3.1 Photovoltaic Power Output Characteristics

Figure 2 illustrates the relationship between solar irradiance and the power output of the proposed photovoltaic (PV) array. As expected, PV power output increases nearly linearly with irradiance, reaching a peak output of approximately 14.85 kW at standard irradiance conditions of 1000W/m2. This trend confirms the adequacy of the selected PV capacity in meeting the system's energy requirements under typical operating conditions. The linear behavior also indicates that the use of MPPT charge controllers effectively enables maximum energy extraction across a wide range of irradiance levels, particularly during partial sunlight conditions commonly experienced during morning and late afternoon hours. The observed surplus power during high-irradiance periods provides a buffer against short-term fluctuations in solar availability and contributes to faster battery recharge, thereby enhancing overall system reliability. This characteristic is particularly important for off-grid operation, where energy balance must be maintained without support from the utility grid.

3.2 Battery State-of-Charge Performance

The dynamic behavior of the battery storage system over a 48-hour operating period is shown in Figure 3. The battery state-of-charge (SOC) exhibits a cyclic pattern that reflects daytime charging and nighttime discharge, consistent with expected system operation. Throughout the 48-hour period, the SOC remains within a safe operating range of approximately 75% to 96%, indicating that the battery bank is neither overcharged nor deeply discharged. Also, the SOC profile demonstrates that the system successfully maintains two-day energy autonomy, even in the absence of continuous solar input. The absence of prolonged low SOC levels suggests that the chosen battery capacity, in combination with PV oversizing, is sufficient to absorb daily charging demands while preserving battery health. This stability supports long-term system durability and reduces the likelihood of premature battery degradation

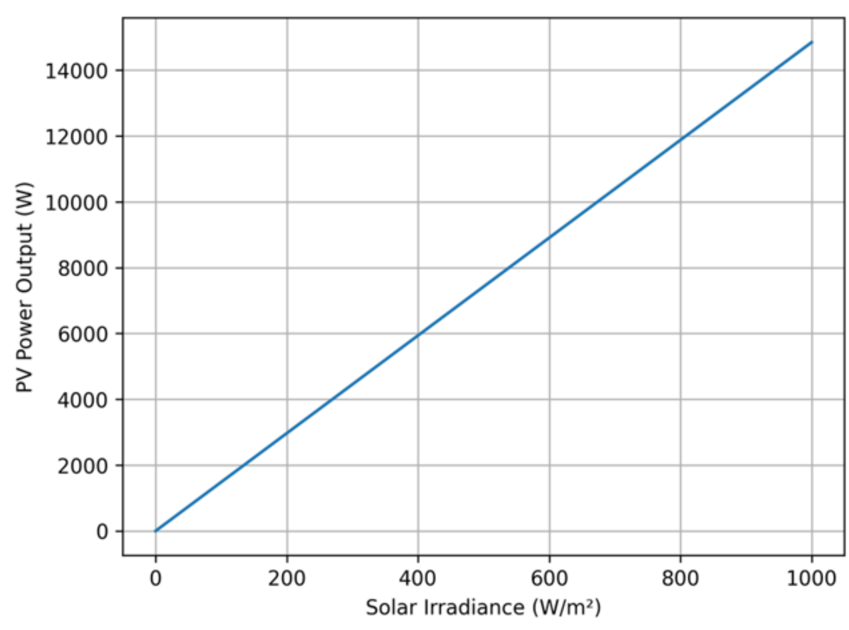

Figure 2: Photovoltaic power output as a function of solar irradiance for the proposed 99-panel solar

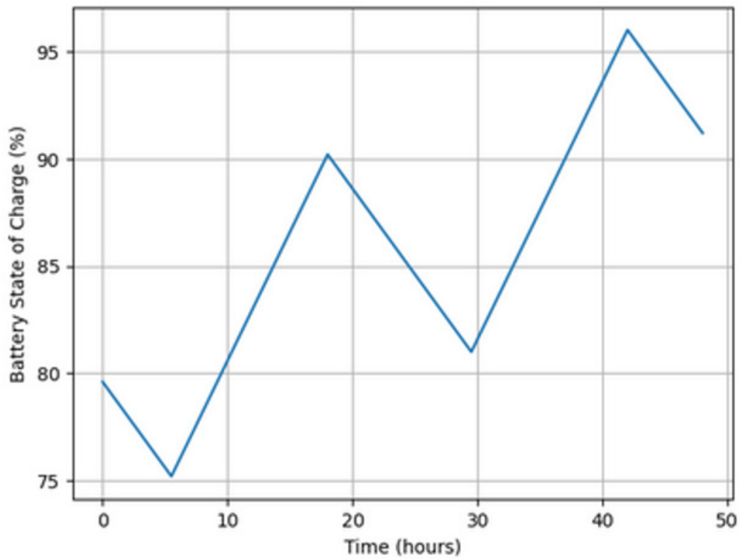

Figure 3: Battery state-of-charge (SOC) profile over a 48-hour operating period under typical solar irradiance and charging demand conditions

3.3 Sensitivity of Battery SOC under Reduced Solar Irradiance

To evaluate system robustness under non-ideal solar conditions, a sensitivity analysis was performed by reducing the effective solar irradiance by 20%. Figure 4 compares the resulting battery SOC profile with that obtained under nominal irradiance conditions. As shown in the figure, reduced irradiance leads to a slower rate of battery charging during daylight hours, resulting in a modest reduction in peak SOC levels. Despite this reduction, the battery SOC remains within acceptable operating limits throughout the 48-hour period, with no occurrence of deep discharge. This result demonstrates that the system possesses sufficient generation margin and storage capacity to withstand short-term reductions in solar availability without compromising charging reliability. The observed resilience is primarily attributed to PV oversizing and conservative battery capacity design, which together enhance operational stability in off-grid conditions.

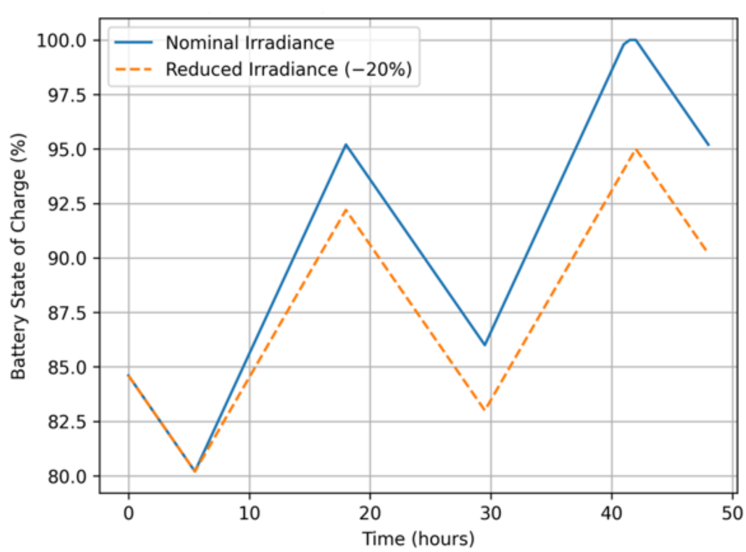

Figure 4: Sensitivity analysis of battery state-of-charge (SOC) under nominal and reduced solar irradiance (−20%) over a 48-hour operating period

3.4 System Reliability and Operational Robustness

In addition, Figures 2 – 4 highlights the reliability of the proposed system under both nominal and stressed operating conditions. Figure 1 confirms adequate energy generation, Figure 2 demonstrates stable storage behavior under normal conditions, and Figure 3 verifies robustness against reduced solar input. Collectively, these results indicate that the system can maintain continuous operation despite variations in irradiance and daily charging demand. The presence of excess energy during peak generation periods further suggests that the system can tolerate moderate increases in charging demand or temporary reductions in irradiance without compromising operational reliability. Also, from a practical perspective, the demonstrated tolerance to irradiance reduction suggests that the system can accommodate seasonal variability and short-term weather disturbances without requiring immediate system expansion. This characteristic enhances the suitability of the proposed design for real-world campus deployment, where operational conditions are inherently dynamic.

3.5 Environmental and Practical Implications

Beyond technical performance, the proposed system delivers measurable environmental benefits. By displacing grid-based or fossil-fuel-dependent charging alternatives, the system achieves an estimated annual carbon dioxide emission reduction of approximately 7.62 tons. This reduction directly links system performance to sustainability objectives and demonstrates the practical impact of integrating renewable energy into campus transportation infrastructure. Overall, the results confirm that the proposed solar-powered e-bike charging system achieves a balanced combination of adequate power generation, reliable energy storage, and operational resilience, making it a technically sound and scalable solution for off-grid or energy-constrained environments.

In broader terms, the system's performance supports environmental and institutional sustainability objectives. By eliminating fossil fuel dependence for e-bike charging, it contributes to reducing annual carbon emissions by over 7.6 tons. The design aligns with Sustainable Development Goals (SDG) 7, 11, and 13, promoting clean energy, sustainable mobility, and climate action within higher education environments. These results highlight the transformative role of integrating renewable energy with campus mobility systems, positioning universities as innovation hubs and catalysts for green technology adoption across Africa.

4. CONCLUSION

This study presented the design and simulation-based evaluation of a fully off-grid solar-powered e-bike charging system intended for campus-scale deployment. The proposed system was analytically sized to support the charging requirements of up to 100 electric bicycles while maintaining two-day energy autonomy under realistic solar irradiance conditions. By integrating photovoltaic generation, battery storage, and power conversion within a unified design framework, the study demonstrated the technical feasibility of reliable e-bike charging without reliance on grid electricity.

Simulation results obtained using MATLAB/Simulink and HOMER Pro confirmed stable system operation across nominal and stressed conditions. The photovoltaic array was shown to provide sufficient energy generation to meet daily demand, while the battery bank-maintained state-of-charge levels within safe operating limits over extended operating periods. Sensitivity analysis under reduced solar irradiance further demonstrated that the system possesses adequate resilience to short-term variations in solar availability, thereby reinforcing the robustness of the proposed design.

Beyond technical performance, the system contributes to sustainability objectives by enabling renewable-powered campus mobility and reducing dependence on fossil-fuel-based electricity sources. The estimated annual carbon dioxide emission reduction highlights the potential environmental benefits of adopting solar-powered e-bike charging infrastructure in institutional environments.

While the present work focused on technical sizing, energy performance, and operational reliability, it did not consider techno-economic optimization or cost–benefit analysis. Such assessments depend strongly on site-specific economic parameters and were therefore beyond the scope of this study. Future work will extend the proposed framework to include location-dependent economic evaluation, experimental validation, and performance assessment under seasonal demand variations.

Overall, the findings demonstrate that a carefully designed off-grid solar-powered e-bike charging system can deliver reliable, resilient, and environmentally beneficial operation at campus scale, providing a practical pathway toward sustainable micro-mobility infrastructure in energy-constrained settings.

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